ETC CE Report 2025/6

# Textiles and the environment – The role of digital technologies in Europe's circular economy

Authors:
ETC experts: Saskia Manshoven, Anse Smeets, Maarten Christis, Tom Duhoux (VITO), Dina Lingås (NORION), Francesca Grossi (CSCP)
EEA experts: Lars Fogh Mortensen, James Clarke

European Environment Agency
European Topic Centre
Circular economy and resource use

Cover design: EEA
Cover image © by kynny on iStock
Layout: ETC CE

**Publication Date** March 2025

**EEA activity** Circular Economy and Resource Use

ETC CE coordinator: Vlaamse Instelling voor Technologisch Onderzoek (VITO)

ETC CE partners: Banson Editorial and Communications Ltd, česká informační agentura životního prostředí (CENIA), Collaborating Centre on Sustainable Consumption and Production (CSCP), Istituto Di Ricerca Sulla Crescita Economica Sostenibile, Istituto Superiore per la Protezione e la Ricerca Ambientale, IVL Swedish Environmental Research Institute, Norion Consult, Università Degli Studi Di Ferrara (SEEDS), German Environment Agency (UBA), Teknologian Tutkimuskeskus VTT oy, Wuppertal Institut für Klima, Umwelt, Energie gGmbH, World Resources Forum Association

European Topic Centre on
Circular economy and resource use
https://www.eionet.europa.eu/etcs/etc-ce

## Contents

1. Introduction ..... 5
2. Trends in production and consumption of textile products in Europe ..... 7
  2.1 Production and consumption trends ..... 7
  2.2 Environmental and climate impacts ..... 22
3. Textiles 4.0: Digital solutions for sustainability and circularity of textiles ..... 29
  3.1 Introduction to Textiles 4.0 ..... 29
  3.2 The use of digital technologies throughout the textiles value chain ..... 30
  3.3 Digital technologies in support of circular business models ..... 46
  3.4 Implementation barriers ..... 53
4. Summary and outlook ..... 57
References ..... 60
Annexes ..... 67
  Annex 1: Definition of textile products ..... 67
  Annex 2: Modelling methodology ..... 67
  Annex 3: Glossary of Digital Technologies and their application in textiles ..... 74
  Annex 4: List of interviewees ..... 77

# Acknowledgements

The report has been produced within the task on ‘Textiles and the environment – the role of digital technologies in Europe’s circular economy’ of the 2024 ETC CE work program. Lars Fogh Mortensen (EEA) has been the project leader and Saskia Manshoven (ETC CE) has been the task leader.

The authors are grateful to the following experts and organisations for their comments that substantially improved the quality of the report:

- Luca Boniolo, ECOS
- Sanna Due, EEA
- Tom Duhoux, VITO
- Mikael Garrelick, DG GROW
- Dries Huygens, JRC
- Marina Prados Espínola, Policy Hub
- Rita Tedesco, ECOS
- Gabriella Waibel, DG ENV
- Carsten Wentink, DG ENV

During the drafting of the report, many industry experts kindly agreed to participate in interviews, which contributed valuable insights in the current state of the art, as well as in the challenges and opportunities associated with the implementation of digital technologies. The interviews were conducted anonymously, but an indicative list of interviewees is included in Annex 4.

# 1. Introduction

The introduction of digital technologies - sometimes called the Fourth Industrial Revolution or Industry 4.0 – induces major transformations in European industry and global value chains. These technologies can take different forms, such as Internet of Things (IoT), Big Data, artificial intelligence (AI), computer-aided design (CAD), 3D printing, blockchain, augmented (AR) and virtual reality (VR) environments, and metaverse (Rantala et al., 2023; Wiegand and Wynn, 2023)[1].

The textile industry has already undergone a significant digital transformation in recent years, integrating Internet of Things applications in textile manufacturing, automating production and logistic processes and meeting the increasing consumer demand for personalised products. The COVID-19 pandemic has further accelerated this need for digitalisation, starting with a surge in e-commerce, but evolving in general into a more digital way of working, a trend that will most likely continue in the future (EURATEX, 2023b). Moreover, digital technologies are widely acknowledged as important enablers of circular business models (Kristoffersen et al., 2020; Antikainen et al., 2018; Bressanelli et al., 2018).

In 2022, the European Commission proposed a comprehensive EU Strategy for Circular and Sustainable Textiles, highlighting the potential of digitalization (European Commission, 2022). In July 2024, the Ecodesign for Sustainable Products Regulation (ESPR) was published, introducing the mandatory development of digital product passports (European Commission, 2024a). Digital technologies can play an important role in circular textiles design, optimisation of production processes, management of new and circular business models, and information sharing and transparency across the value chain (Wynn and Jones, 2022). Additionally, the new Competitiveness Compass for the EU will 'guide the work in the coming five years and lists priority actions to reignite economic dynamism in Europe' (European Commission, 2025). The textiles and clothing sector in the EU is a significant contributor to our competitiveness, generation of value added and employment. Innovation in textiles production and consumption – including through digitalisation – and decarbonising the textiles industry can contribute to boosting EU competitiveness.

From the perspective of the circular economy, the functionalities offered by digital technologies and data analytics can possibly deliver necessary information to inform decision-making and optimisation processes to increase resource efficiency, extend product lifetimes through circular design, maintenance and repair, and to close product and material loops (Antikainen et al., 2018; Bressanelli et al., 2018). However, while these technologies have the potential for increased circularity and sustainability, also risks and trade-offs arise, spurring the need for thorough assessments on whether they really reduce negative environmental and climate impacts related to textiles production and consumption. Also, there may be certain social impacts involved, for example related to changes in employment and consumption behaviour.

This report explores the role of digital technologies in the transition to a circular textiles system. It is structured as follows.

Chapter 2 provides an update of previously published data and knowledge (ETC/CE, 2022, 2023, 2024a; ETC WMGE, 2019; ETC/WMGE, 2021). EU policies on textiles, including the EU Strategy and Sustainable and Circular Textiles, the Ecodesign for Sustainable Products Regulation (ESPR), have been informed by data and knowledge provided by the EEA. In order to continue to inform the development and implementation of EU policies on textiles, selected data and knowledge have been updated in this report. Most recent trends in European textiles production, consumption, trade and export of used textiles are explored, using public data from Eurostat, other sources and literature. Environmental impact estimations are made based on input-output modelling using FIGARO v.2024 and Exiobase v3.8.2.

---

[1] Annex 3 contains a glossary of digital technologies discussed in this report

Moreover, this task also draws upon the new textile module developed and published in the EEA Circularity Metrics Lab (CML).

Chapters 3 explores the role of digital technologies in Europe's circular economy for textiles. The report provides an overview of digital tools (both existing and emerging) and investigates their potential for changing the way how, among others, clothing and other textiles are designed, manufactured, and serviced, how they can enable new ways for brands, retailers and consumers to interact, reduce returns, trace products across the entire lifecycle and enable circular business models. The research starts from a systematic literature and practice review of scientific and grey literature. Findings from literature are enriched by semi-structured interviews with 19 European textiles and fashion companies and SMEs, as well as sector organisations and expertise centres on sustainable textiles (listed in Annex 4). Based on these findings, the potential contribution of these technologies to resource efficiency, lifetime extension of products, reuse and high-quality recycling is discussed. It also considers potential drawbacks and negative effects on the environment and climate. The study also focuses on how these technologies will contribute to circular business models for textiles. Based on literature and interviews, it identifies the barriers that companies face when trying to implement them and highlights some of the socio-economic impacts that the digital transformation may have, as well as policies needed to support the transition.

Chapter 4 provides a summary of the main insights of this report and an outlook on future developments.

# 2. Trends in production and consumption of textile products in Europe

This chapter updates selected data and analyses previously published by the EEA in several reports (ETC/CE, 2022, 2023, 2024a; ETC WMGE, 2019; ETC/WMGE, 2021; EEA, 2019, 2021, 2022, 2023, 2024).

As a result of a new modelling approach and new data sources, the absolute impact values in this report differ to some extent from those reported in the previous reports. It is important to note that the results need to be considered more as 'orders of magnitude' and 'indicative trends', rather than as absolute quantities. The methodology that is used in the current report is briefly described in Box 1 and a more detailed analysis of the differences with previously reported data is discussed in Annex 2.

**Box 1 Methodology**

The data for analysing the trends in production and consumption of textile products in Europe are mainly based on available ESTAT EU27 production and trade data (i.e., EU27 trade with extra-EU27 partners), and on footprint calculations of EU27 household consumption.

While previous results reporting on the role of EU27 textile consumption in global environmental impacts were based on EXIOBASE (update was based on a modified version of EXIOBASE v3.8.1), this report makes use of the ESTAT FIGARO tables.

In the study 'Textiles and the environment in a circular economy' (EEA, 2019; ETC WMGE, 2019), calculations were based on the EXIOBASE v.3.4 model, extrapolating consumption data from 2011 to 2017 (Stadler et al., 2018). In the study 'Textiles and the environment – the role of design in Europe's circular economy' (ETC/CE, 2022; EEA, 2022), these environmental impacts were updated using the EXIOBASE v3.8.1 model, combined with the actual 2020 consumption data from Eurostat. The production and consumption reductions due to the COVID-19 crisis caused 2020 data to be lower than would have been expected in a 'business as usual' scenario. Therefore, 2019 data were always presented as a comparison. Consumption data from other years were modelled by EXIOBASE itself.

This report makes use of the ESTAT FIGARO tables. Environmental and social extensions are added using data from ESTAT, Air emission accounts by NACE Rev. 2 activity [env_ac_ainah_r2], last update 04/07/2024 and from EXBIOASE v3.8.2. Both the improved quality of the FIGARO model and its annual updates make together that the choice for this model is well-founded. However, the shift to this model does have an impact on the comparison of the results of this study with previous studies. Numerous changes complicate a precise description of the changes and comparability between results. However, the differences in the allocation of final demand into consumption domains, of which textiles is one, has an impact on the results. More details are provided in Annex 2.

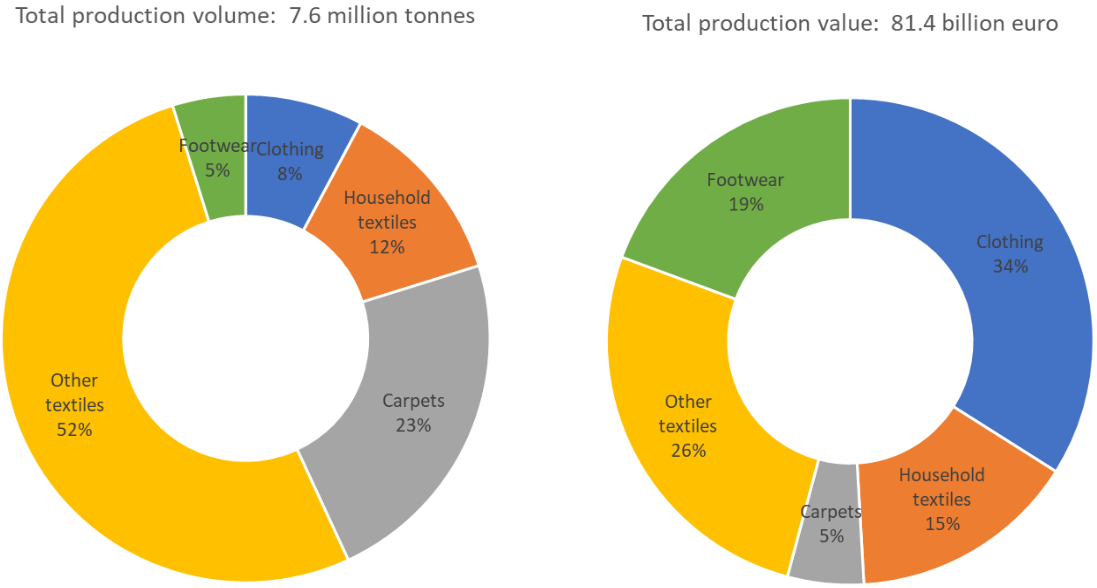
## 2.1 Production and consumption trends

### EU production of textiles

In 2023, the EU textile and clothing sector had a turnover of EUR 170 billion, employing about 1.3 million people across 197 000 companies. 99.7 % of European companies active in textiles and clothing are micro-enterprises (0-9 employees) or SMEs (10-249 employees), highlighting the fragmented nature of the sector (EURATEX, 2024). Two thirds of these companies are active in the sub-sector of clothing. After the major drop in turnover following the COVID-19 pandemic in 2020 (-9 % for textiles as a whole and -17 % for clothing, (Euratex, 2021)), current numbers show that the sector has recovered to pre-COVID-19 levels (EURATEX, 2024; ETC/CE, 2022)

In 2022, 7.6 million tonnes of finished textile products[2] were produced in EU27[3], representing a value of EUR 81 billion (Figure 2.1). EU production specialises in technical textiles (including non-wovens, technical and industrial textiles, ropes and fabrics for use in healthcare, agriculture, sportswear, automotive etc.), but also in high-value clothing and footwear. While finished products (clothing and footwear, household and interior textiles, industrial and technical textiles) represent around three quarters of output value of the European textiles sector, the EU is still a significant producer of intermediate products, such as fibres (6 % of output value), yarns (5 %) and fabrics (14 %) (EURATEX, 2024).

**Figure 2.1 Production of textile related products in EU27, 2022, million tonnes and billion EUR**



**Source:** ESTAT, Sold production, exports and imports [DS-056120], last update 30/08/2024. Physical unit others than in kilogram are converted into kilograms using conversion factors from Annex 6 of the Economy-wide material flow accounts (EW-MFA) – Annexes to the 2024 questionnaire. Definitions of the textile products are explained in Annex 1.

After the drop in EU27 production volumes and value in 2020, the sector as a whole has recovered to pre-COVID-19 production value levels (Figure 2.2). However, the increasing trend in production volumes in the EU can no longer be seen after 2021.

In addition, relative changes between product types can be noticed. Compared to 2019, the production in 2022 of clothing has decreased (-23 % in volume, -15 % in value), as has production of carpets (-3 % in volume, -9 % in value) and footwear (-4 % in volume, -16 % in value). On the other hand, production of household textiles (+ 8% in volume, +21 % in value) and other textiles[4] (+ 3% in volume, +9 % in value) have increased.

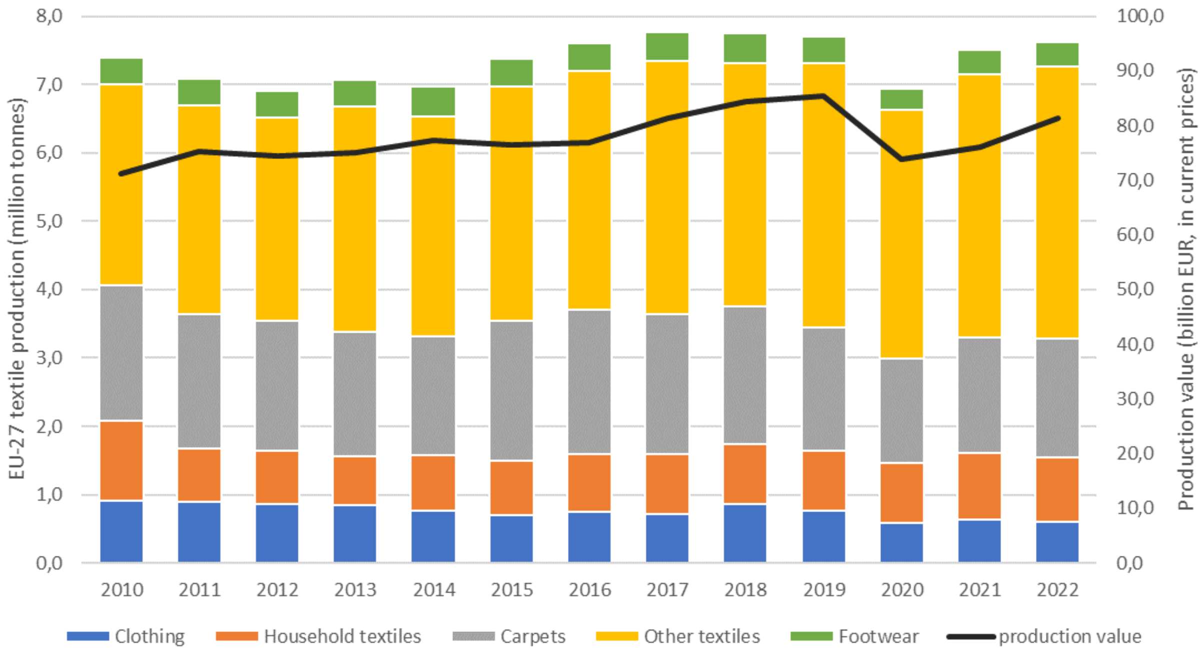
---

[2] Terminology to describe different groups of textile products is explained in Annex 1

[3] Textile product types are reported in several different units in Eurostat. Volume estimates (in kg) for the different product types were calculated using the conversion factors provided by Eurostat.

[4] See Annex 1 for an overview

### Figure 2.2 EU27 production of textile related products, 2010-2022, in million tonnes and billion EUR



**Source:** ESTAT, Sold production, exports and imports [DS-056120], last update 30/08/2024. Physical unit others than in kilogram are converted into kilograms using conversion factors from Annex 6 of the Economy-wide material flow accounts (EW-MFA) – Annexes to the 2024 questionnaire. Definitions of the textile products are explained in Annex 1.

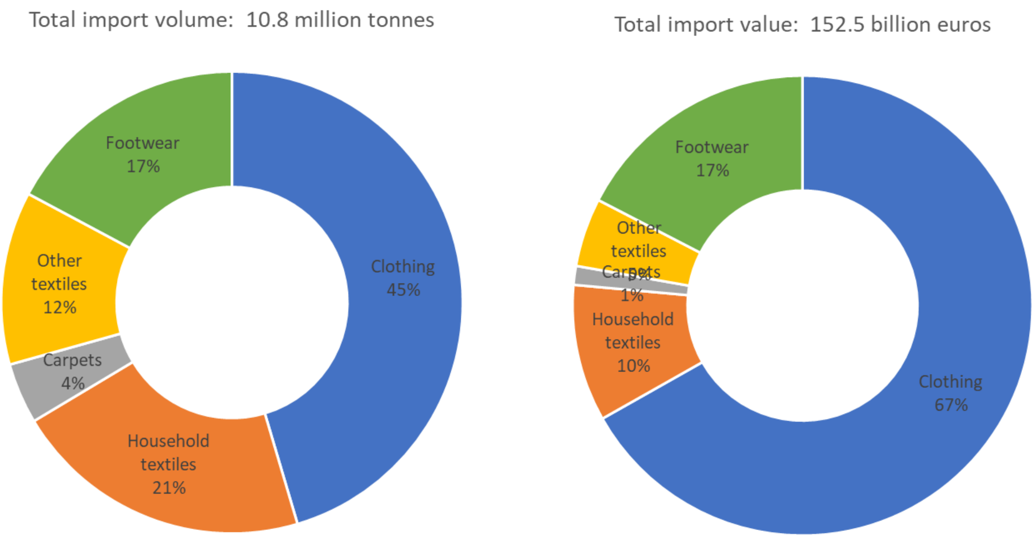
### EU trade

In 2022, Europe imported 11 million tonnes of finished textile products, representing a value of EUR 153 billion[5]. Clothing accounts for almost half (45 %) of imports in terms of volume, before household textiles (21 %), footwear (17 %) and other textiles (12 %). In terms of trade value, around two-thirds (67 %) of import value are generated by import of clothing, while footwear accounts for 17 % (Figure 2.3). The EU imports mainly from China, Bangladesh and Turkey (EURATEX, 2024).

---

[5] Only extra-EU27 trade is included in the numbers, i.e. trade between EU27 member countries and non-EU27 countries. Trade between EU27 member countries is excluded.

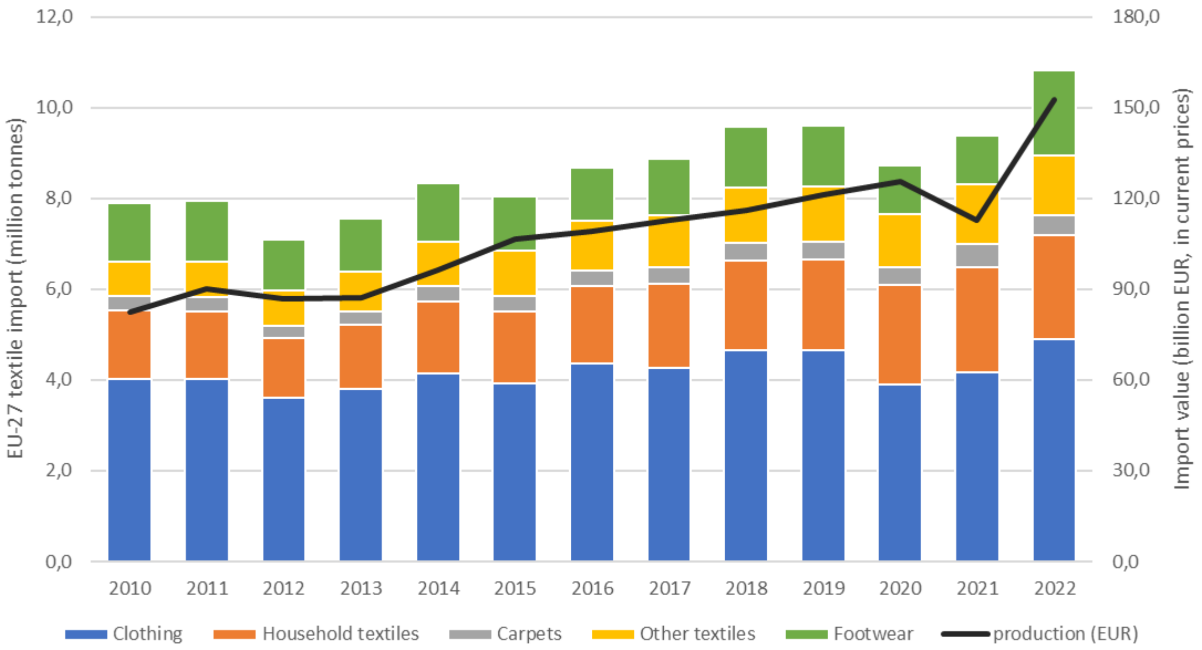
**Figure 2.3 Import of textile related products in EU27, 2022, million tonnes and billion EUR**



**Source:** ESTAT, EU trade since 2002 by CPA 2.1 [DS-059268], last update 16/09/2024. Definitions of the textile products are explained in Annex 1.

After a drop in import volumes in 2020, imports have recovered and significantly increased in 2021 and 2022 (Figure 2.4). The 2020 drop was caused by significantly reduced imports of clothing (-16 %) and footwear (-19 %) during the COVID-19 pandemic, however, the import of household textiles increased in that year by 10 % in volume. By 2022, textile imports regained their increasing trend from pre-COVID-19 times. The value of the imported clothing and footwear items increased more strongly than the volumes. Depending on the product type, a 24-39 % value increase, in current prices, in comparison with 2019 could be observed. A major increase in the import volumes of footwear can be observed, imported volumes increased by 39 % between 2019 and 2022, but only showed a 25 % increase in terms of value.

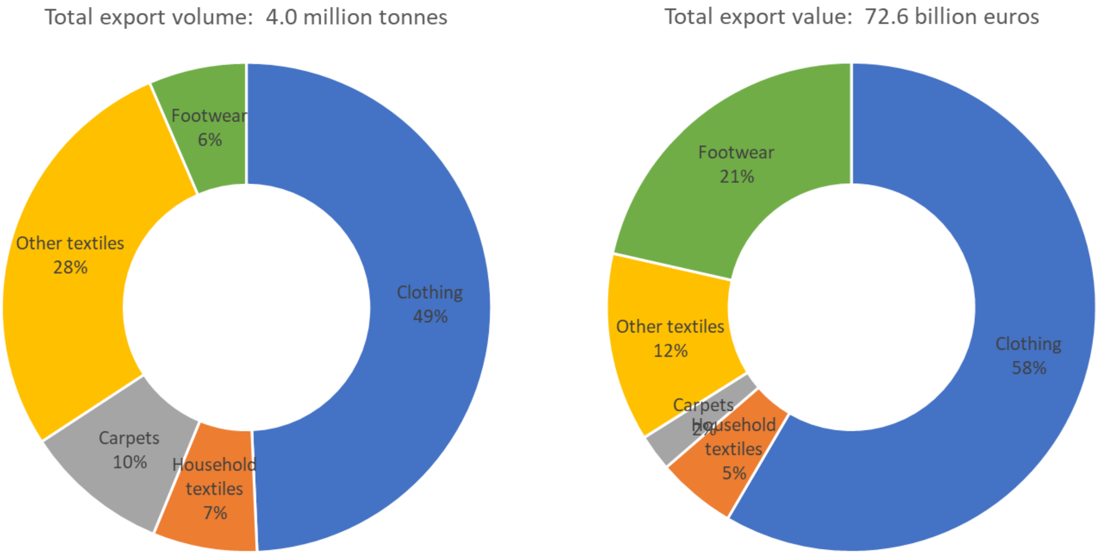
**Figure 2.4 Import of textile related products in EU27, 2010-2022, million tonnes and billion EUR**



**Source:** ESTAT, EU trade since 2002 by CPA 2.1 [DS-059268], last update 16/09/2024. Definitions of the textile products are explained in Annex 1.

Regarding exports, in 2022, 4.0 million tonnes of finished textiles were exported, representing a value of EUR 73 billion[6]. Clothing and footwear together represent 80 % of the export value, but only 56 % in terms of volume. On the other hand, 'other textiles' (non-wovens, industrial textiles, ropes, etc.) represent 28 % in terms of volume, but only 12 % in terms of value (Figure 2.5). Switzerland and UK are EU's main export markets, closely followed by US and also China (EURATEX, 2024).

### Figure 2.5 Export of textile related products in EU27, 2022, million tonnes and billion EUR



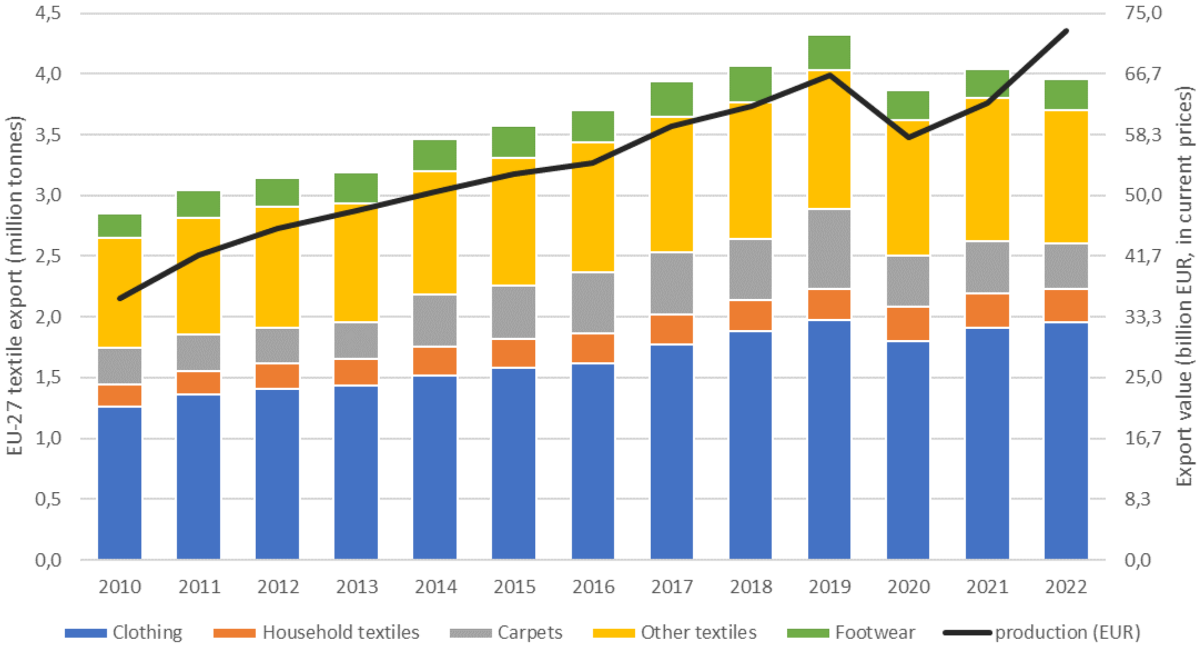
**Source:** ESTAT, EU trade since 2002 by CPA 2.1 [DS-059268], last update 16/09/2024. Definitions of the textile products are explained in Annex 1.

Export volumes have been decreasing over the past few years (-8 % in comparison to 2019), despite a slight recovery in 2021. At the same time, export value, in current prices, has significantly increased despite decreasing volumes (+ 9% in comparison to 2019) (Figure 2.6). While the export volume decrease can be observed over all product types, the increase in export value is most significant for household textiles and other textiles (+20 % and +15 % respectively).

---

[6] Only extra-EU27 trade is included in the numbers, i.e. trade between EU27 member countries and non-EU27 countries. Trade between EU27 member countries is excluded.

**Figure 2.6 Export of textile related products in EU27, 2010-2023, million tonnes and billion EUR**



**Source:** ESTAT, EU trade since 2002 by CPA 2.1 [DS-059268], last update 16/09/2024. Definitions of the textile products are explained in Annex 1.

### EU consumption of textiles

In 2022, European households spent a total of EUR 375 billion on textiles, of which EUR 278 billion on clothing. On average, per person, the expenditure was EUR 621 on clothing, EUR 147 on footwear and EUR 71 on household textiles[7]. While textile expenditures dropped significantly in 2020 and 2021, they increased significantly again in 2022, continuing the trend from before the COVID-19 crisis (+1 % in comparison with 2019). However, the relative share of textiles in the total household expenditure has not changed over the last decade, it remains at 5 %. Similarly, the expenditure distribution among clothing, footwear and household textiles has remained constant, except during the COVID-19 pandemic (2020-2021), the share of household textiles temporarily increased.

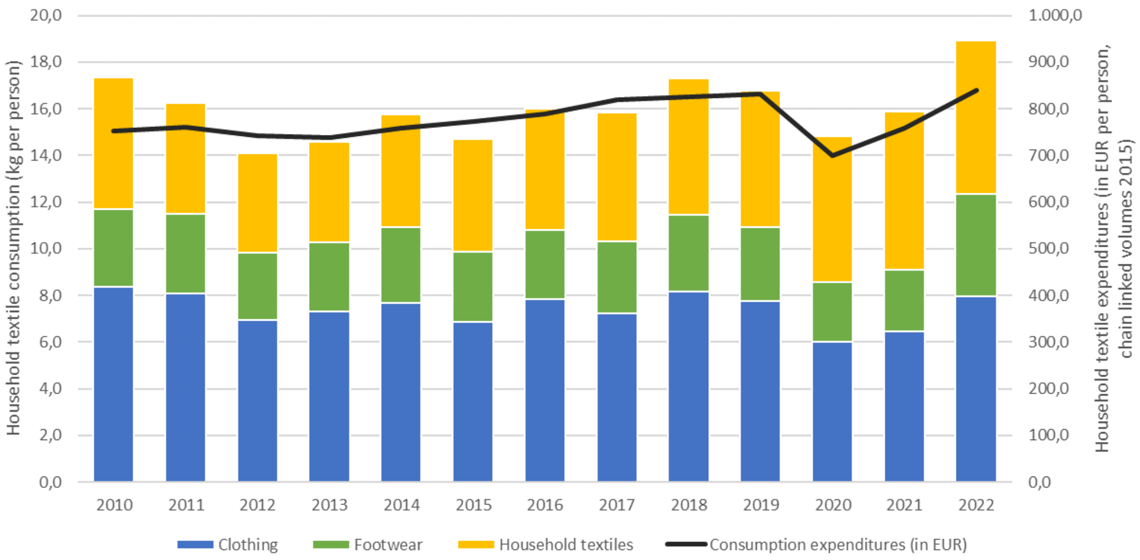
Textiles consumption volumes are difficult to estimate and come with a high degree of uncertainty. Different studies have yielded different numbers, ranging from 12-25 kg per person per year (ETC WMGE, 2019; ETC/CE, 2022). When calculating the 'apparent consumption'[8] based on Eurostat production and trade data – and excluding industrial/technical textiles and carpets - a total 'apparent' textiles consumption for 2022 of 19 kg per person per year is estimated, consisting of, on average, about 8 kg clothing, 7 kg household textiles and 4 kg footwear (Figure 2.7). In the period 2010-2022, the apparent consumption of textiles fluctuated between 14 and 19 kg per person per year.

---

[7] ESTAT, Final consumption expenditure of households by consumption purpose (COICOP 3 digit) [nama_10_co3_p3], last update 25/09/2024. Textile consumption includes consumption domains 03.1, 03.2 and 05.2.

[8] Apparent consumption = production + import - export

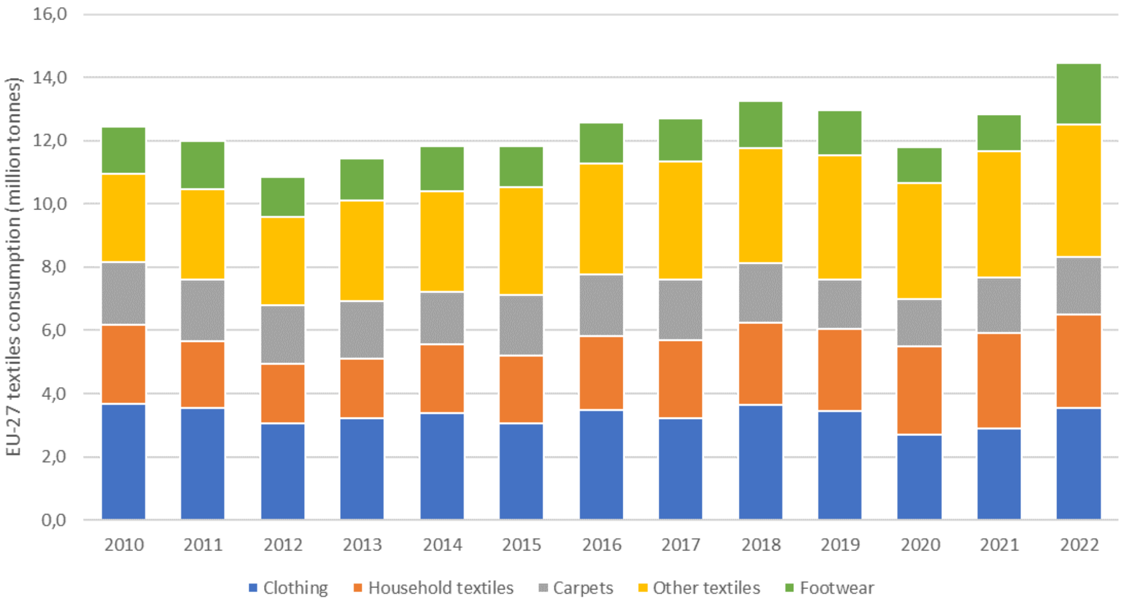
**Figure 2.7 EU27 apparent consumption of clothing, footwear and household textiles (excluding carpets and other textiles) (calculated as production + import – export), 2010-2022, kilograms per person and EUR per person**



**Source:** ETC-CE calculations based on ESTAT, Final consumption expenditure of households by consumption purpose (COICOP 3 digit) [nama_10_co3_p3], last update 25/09/2024, ESTAT, EU trade since 2002 by CPA 2.1 [DS-059268], last update 16/09/2024, and ESTAT, Sold production, exports and imports [DS-056120], last update 30/08/2024.

Looking at the apparent consumption for all textiles in terms of volumes (kilograms) (Figure 2.8), a fluctuating consumption volume can be observed, which slightly increased between 2010 and 2022. The composition of textiles product groups changed over time: the volume of clothing decreased from 30 % in 2010 to 25 % in 2022, while the share of other textiles increased from 22 % in 2010 to 29 % in 2023. The other categories remained rather stable.

**Figure 2.8 EU27 apparent consumption of textile products (calculated as production + import – export), 2010-2022, million tonnes**



**Source:** ETC-CE calculations based on ESTAT, EU trade since 2002 by CPA 2.1 [DS-059268], last update 16/09/2024, and ESTAT, Sold production, exports and imports [DS-056120], last update 30/08/2024.

The importance of e-commerce for the textile industry is growing. The percentage of turnover generated by online sales of textiles and clothing more than doubled from 5 % in 2009 to 11 % in 2022 (EURATEX, 2023a). Also, within online sales, clothing takes up the largest share. In 2022, 42 % of online purchases of goods were clothes (including sports clothing), shoes or accessories (Eurostat, 2023).

E-commerce has greatly enhanced accessibility and convenience, including lower prices, greater product variety and wider outreach of online marketing. However, this comes with downsides in terms of sustainability (United Nations Conference on Trade and Development (UNCTAD), 2024). Increased availability of items through e-commerce, as well as addictive designs of e-commerce platforms (European Commission, 2024b) have boosted consumption, encouraging more frequent purchases across different platforms and retailers, provoking impulse buying and overconsumption. Moreover, since consumers cannot try on the items they purchase through e-commerce, some tend to buy the same product in different sizes to try on at home, returning the products that do not fit. The adoption of lenient return practices have also resulted in an increased proportion of returns, of which 22-44% never reaches a new customer and is destructed (ETC/CE, 2024a; Roichman et al., 2024). Additionally, access to online stores across the globe has increased transportation emissions and waste (United Nations Conference on Trade and Development (UNCTAD), 2024).

### EU employment and added value

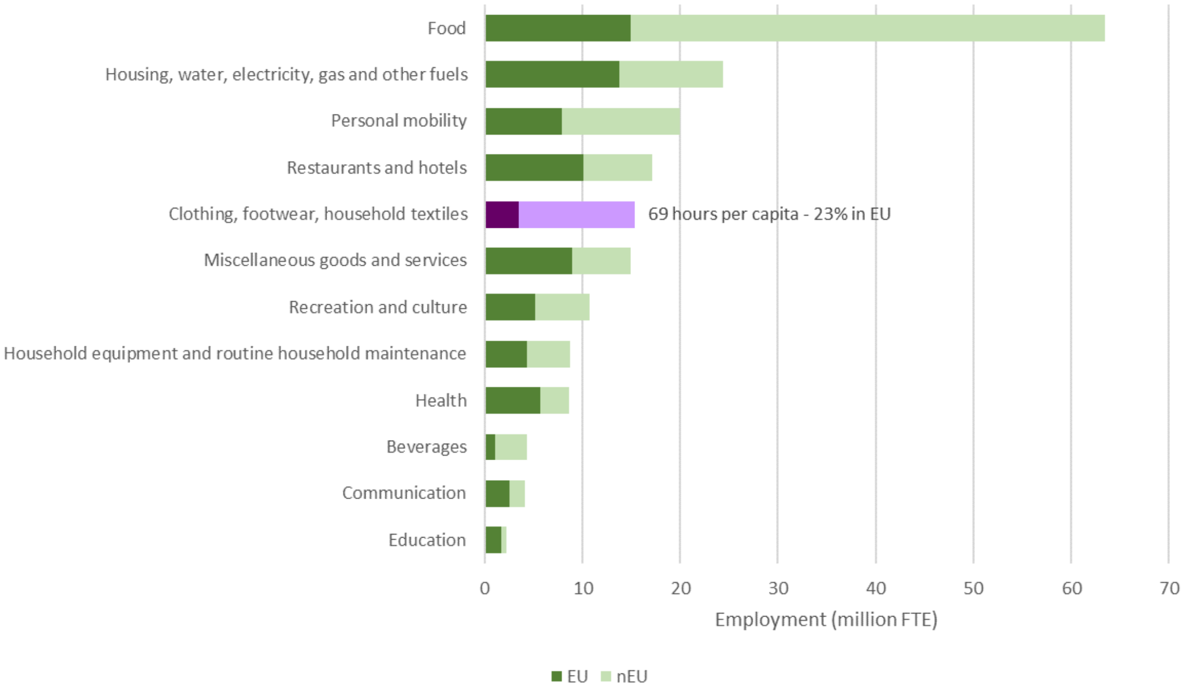
With regard to employment in the value chains, the textiles sector ranks fifth compared to other household consumption domains, after food, housing, and mobility and at relatively equal level with hotels and restaurants, and miscellaneous goods and services (Figure 2.9). To produce the amount of clothing, textiles and footwear consumed by households in the EU27 in 2022, around 15 million full-time equivalents (FTE)[9] were employed worldwide throughout the supply chain. Only 23 % of this employment takes place in Europe, with Italy (24 %), Poland and Portugal (both 10 %) among the top contributors (EURATEX, 2024).

This low share of European employment in the upstream supply chain of EU household consumption of textiles[9] makes the textiles industry stand out in comparison with other industries which have a much larger European employment share; except for the food and beverage sectors (23 % and 24 %, respectively) (Figure 2.9). This share of European employment has remained relatively constant over the past decade. Total employment gradually dropped between 2010 and 2016 but seems to be gradually rising since (Figure 2.10). Women represent more than 71 % of all employees in the value chain, and 42 % of employees is over 50 years old, a share that has gradually increased over time (EURATEX, 2024).

---

[9] 1 FTE = 2,000 working hours per year

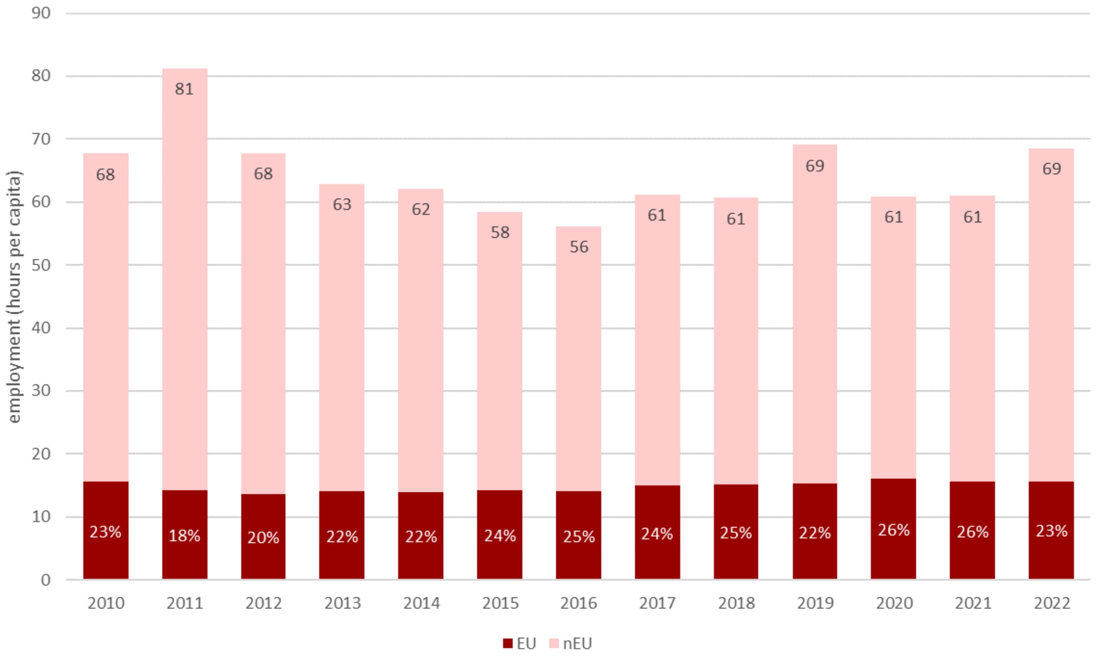
### Figure 2.9 The use of employment in the upstream supply chain[10] of EU household consumption domains, FTE (1 FTE = 2,000 working hours), 2022.



* Note: Informal employment is not included in the data.

**Source**: ESTAT, FIGARO tables (2024-edition) combined with ESTAT, Air emission accounts by NACE Rev. 2 activity [env_ac_ainah_r2], last update 04/07/2024 and EXBIOASE v3.8.2 to add environmental and social extension data.

### Figure 2.10 Use of employment in the upstream supply chain of EU textiles consumption, billion working hours and hours per person, 2010-2022.



* Note: Informal employment is not included in the data.

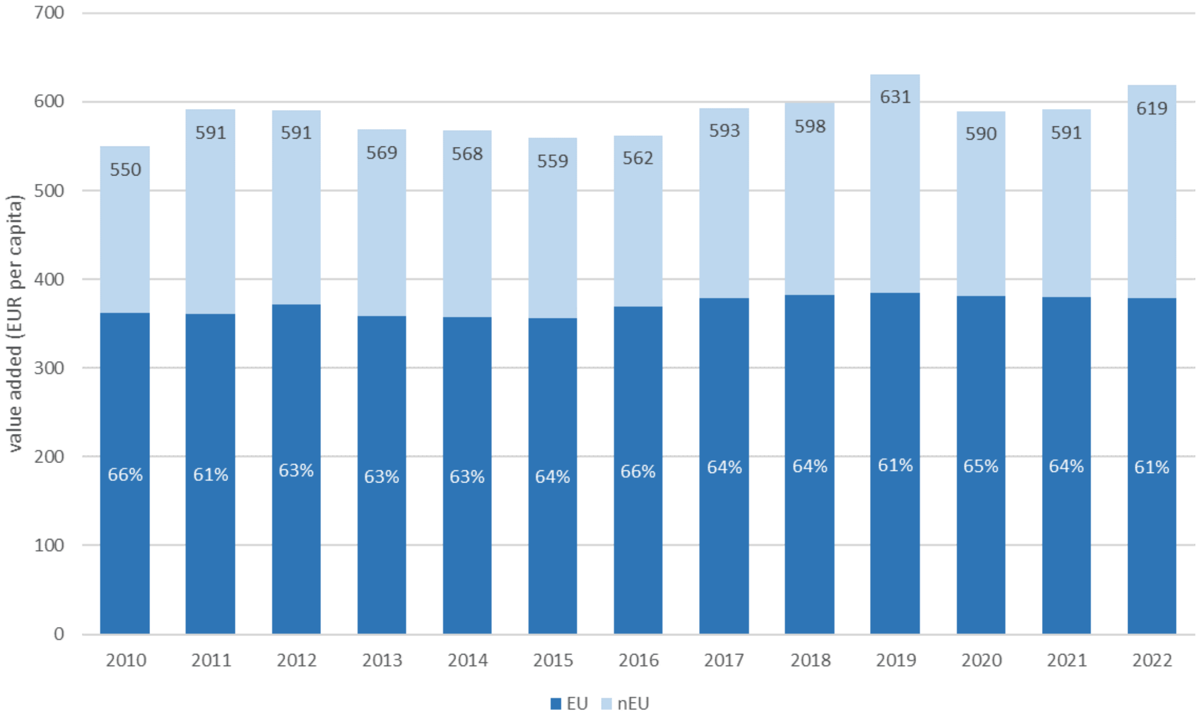
**Source:** ESTAT, FIGARO tables (2024-edition) combined with ESTAT, Air emission accounts by NACE Rev. 2 activity [env_ac_ainah_r2], last update 04/07/2024 and EXBIOASE v3.8.2 to add environmental and social extension data.

---

[10] This includes all activities in industrial and service sectors in the production and supply chain of the textile products up to purchase by households. It excludes the use of the textile products and the treatment at end of life.

Looking at the share of added value created in Europe, it remains relatively constant over the last decade, at around 61-66 % (Figure 2.11). Comparing this with the employment share of 24 % implies that high-value activities (including retail) are mainly taking place in Europe.

**Figure 2.11 Added value in the upstream supply chain of EU textiles consumption, billion EUR and billion EUR per person, current prices, 2010-2022.**



**Source:** ESTAT, FIGARO tables (2024-edition) combined with ESTAT, Air emission accounts by NACE Rev. 2 activity [env_ac_ainah_r2], last update 04/07/2024 and EXBIOASE v3.8.2 to add environmental and social extension data.

## EU waste and exports of used textiles

The export of used textiles nearly tripled over two decades, from a little over 550 000 tonnes in 2000, to 1.4 million tonnes[11] in 2019 (ETC CE, 2023). Since then, the export volume has remained relatively constant, representing 1.37 million tonnes in 2023. However, this volume is expected to rise due to the requirement on all EU Member States to separately collect textile waste by 2025. As of 2024, it is already mandatory to collect textiles separately in more than half of the EU27 Member States. Main importers of European used textiles are in Africa and Asia, with the latter taking up an increasing share. While exports to Africa and non-EU Europe are presumably meant for reuse, exports to Asia are sold at lower prices, suggesting their quality is lower and they are more likely to be recycled rather than reused (ETC/CE, 2023).

The following sections provide an updated overview of the volumes and destinations of used textiles from the EU for 2020 – 2023 and compares these trends with the period 2000-2019. The method used is described in Box 2.

---

[11] Amount without UK which left EU in 2020

### Box 2 Method for updating data for EU exports of used textiles

This update covers the export from the EU27 Member States from 2020 – 2023. The ETC CE report of 2023 was based on data from 'Comtrade' and more specifically the CN-codes 6309 and 6310. Data from Comtrade was however not available for this update, and data for this report was retrieved from the database on International Trade in Goods (ITG), the 'Comext database', which is part of Eurostat. Different from Comtrade, Comext used SITC codes. To ensure comparability between the ETC CE report of 2023 and this update, the SITC codes corresponding to the previously used CN-codes were used, namely 269.01 and 269.02.

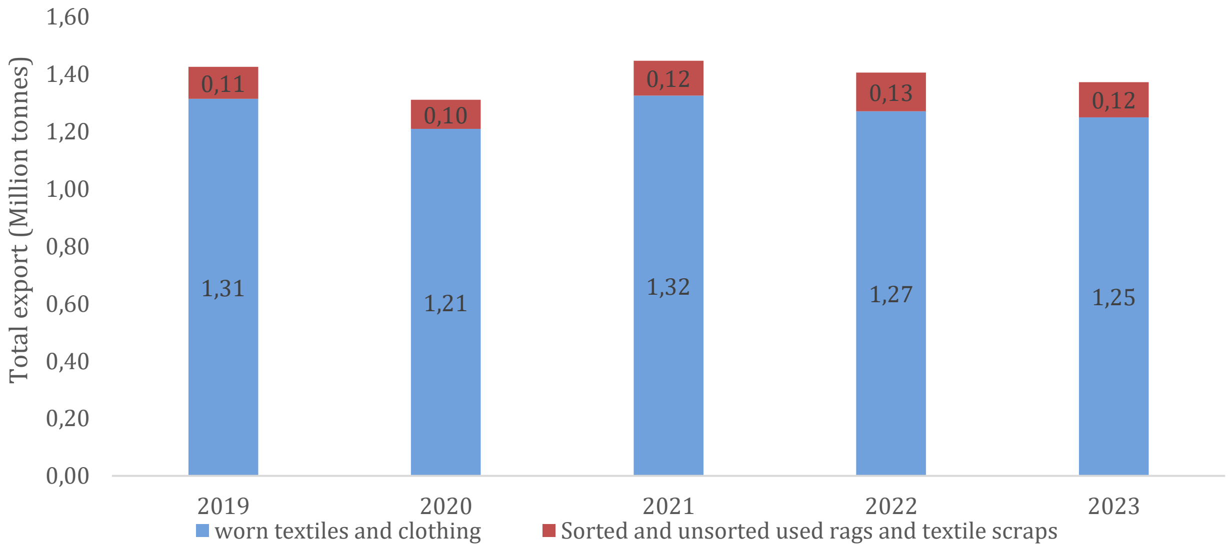
To make it easier for the reader to follow the development from the ETC CE report of 2023 this report nonetheless uses the codes and names from the CN-product code system, namely:

- '6309 – *worn textiles and clothing'* (corresponding to SITC 269.01)
- '6310 – *sorted and unsorted used rags and textile scraps'* (corresponding to SITC 269.02)

*Export volumes*
Between 2000 – 2019, the combined export of '6309 – *worn textiles and clothing'* and '6310 – *sorted and unsorted used rags and textile scraps'* more than tripled to 1,42 million tonnes[12]. Over 2020-2023, this combined amount has remained relatively stable, amounting to 1,37 million tonnes in 2023 (Figure 2.12).

From 2000 – 2019, the share of rags and scraps in the total volume of exported textiles was relatively low, but stable and this trend continued in 2020 – 2023 with a share of between 10 – 13 % of total combined export, (Figure 2.12). Most of the exports are thus worn textiles and clothing, which are believed to be exported for reuse (ETC/CE, 2023).

**Figure 2.12 Export of 'worn textiles and clothing' and 'sorted and unsorted used rags and textile scraps', in million tonnes, from the EU27 from 2019 - 2023**



**Source**: Comext (Accessed 26.04.2024).

---

[12] Original amount of EU28 exports in 2019 was 1,7 million tonnes. To allow a meaningful comparison with recent data, this number is recalculated for EU27 (without UK). UK exports represented 17,5% of EU exports in 2019.

*Export destinations for used textiles from the EU*
In 2000, the EU exported predominantly to Africa (60 %), and less to Asia (28 %)[13]. However, the share of exports going to Asia has gradually increased over time. In 2019, 48 % was exported to Africa and 37 % to Asia[14], with only around 10 % being exported to non-EU European countries (EEA, 2023; ETC/CE, 2023). By 2023, Asia increased its share further, resulting in Africa and Asia being almost equal in share of exports, 45 % and 43 %, respectively (Figure 2.13).

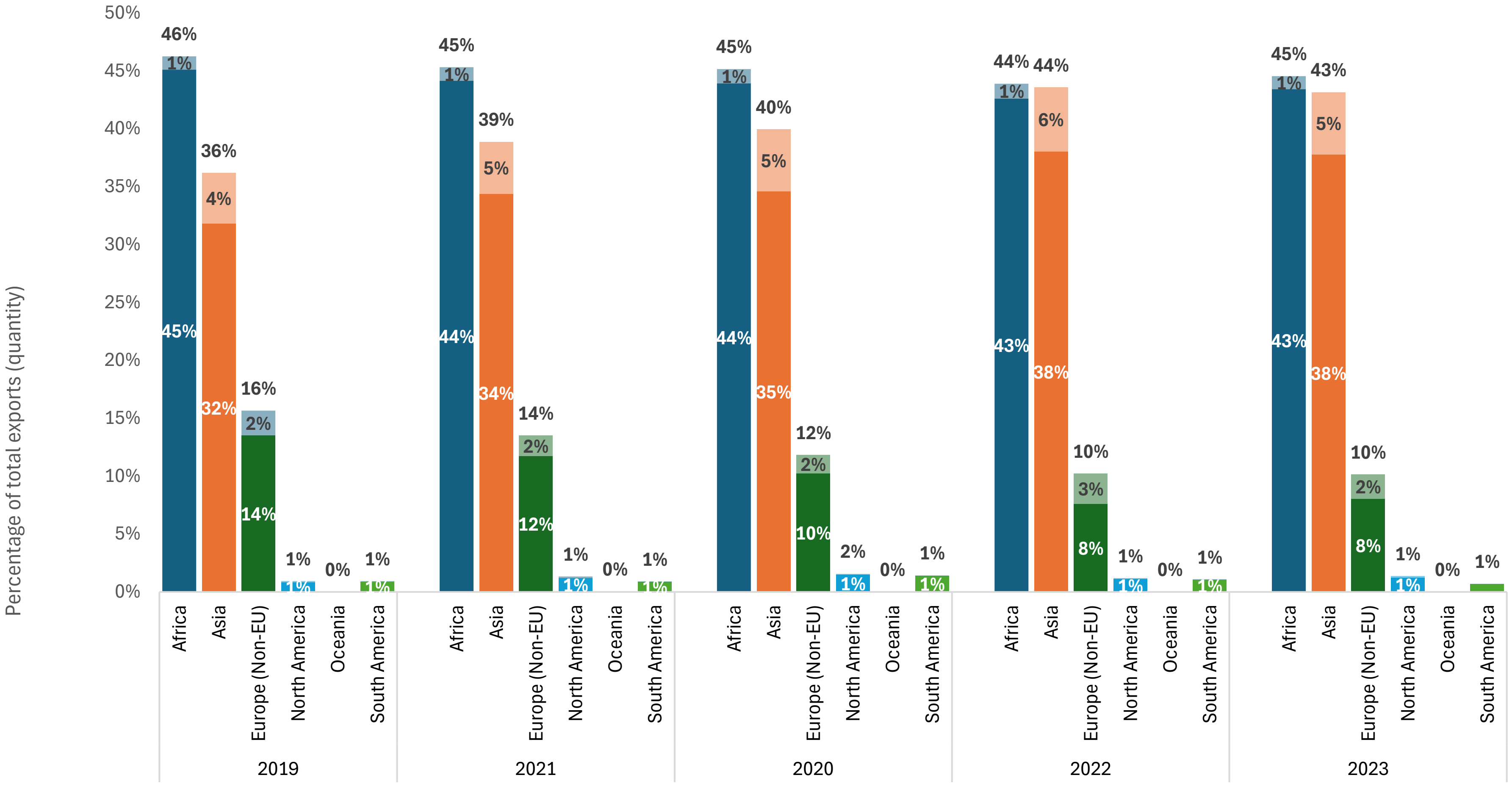
As worn textiles and clothing make up most of the exports, Asia is in fact also importing a significant share of the worn textiles and clothing, which are supposedly indented for reuse, despite largely focusing on recycling and re-export. A possible explanation could be that they re-export sorted textiles, potentially also to Africa.

---

[13] Numbers including UK, since it was part of EU28

[14] Numbers excluding UK, which left EU after 2019. Including UK in the numbers gives slightly differnt numbers: 48% to Africa and 41% to Asia, suggesting that the UK was responsible for a significant share of the export to Asia.

**Figure 2.13 Extra EU exports of used textiles (‘worn textiles and clothing’ and ‘textile rags and scraps’), in percentage of quantity, by receiving continent, 2019 - 2023**

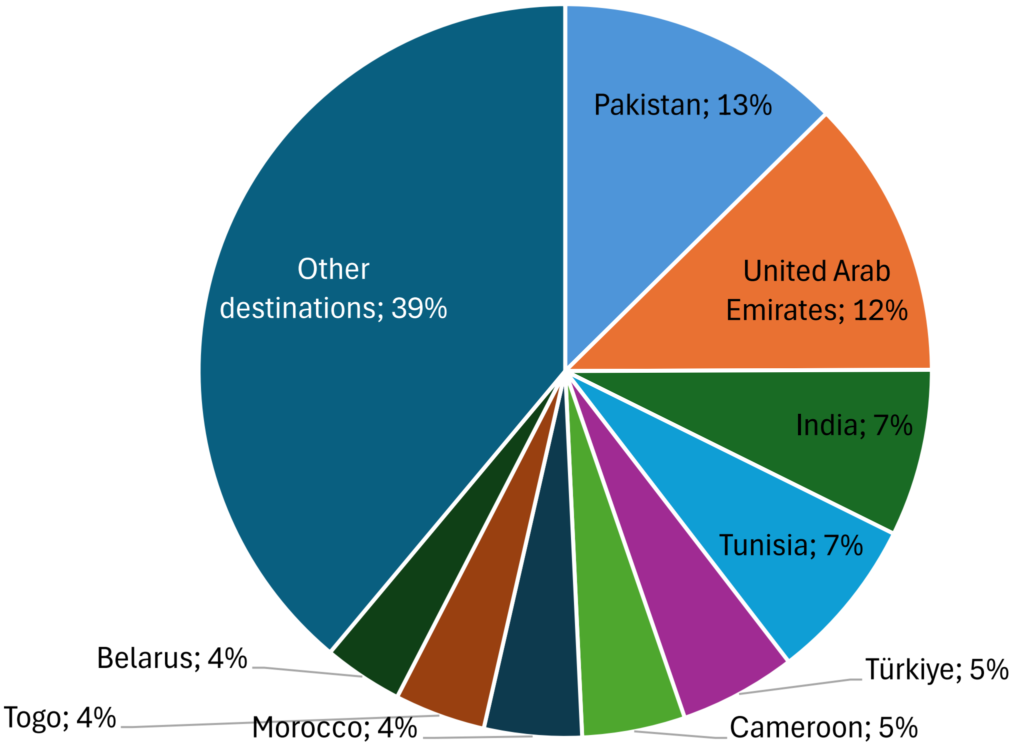


* Note: The bars for Africa, Asia and Europe (Non-EU) consist of two colour shades. The darker shade represents CN-code ‘6309: *worn textiles and* clothing’ and the lighter shade represents ‘6310: *sorted and unsorted used rags and textile scraps’*. The percentage above the bar is the total share of used textiles from EU27 imported by the continent.
**Source**: Comext (Accessed 26.04.2024).

Figure 2.13 shows that the EU is consistently exporting the majority of '6309 – *worn textiles and clothing*' to Africa, although an increasing share of the exports go to Asia. On the contrary, the majority of '6310 - *sorted and unsorted used rags and textile scraps',* which is only a small share of the total exports, goes to Asia. This indicates that, imported textiles to Africa are mostly meant for reuse (focus on '6309 – *worn textiles and clothing')*, whereas the textiles exported to Asia are supposedly largely meant to be recycled or re-exported ('6310 - *sorted and unsorted used rags and textile scraps')* although it is also increasingly importing (supposedly) reusable fractions (EEA, 2023; ETC/CE, 2023). Unfortunately, the actual fate of these exported textiles is largely unknown.

Regarding the receiving countries of the exported used textiles, an increased specialisation can be observed, meaning that fewer countries are importing a growing share of EU exports (EEA, 2023; ETC/CE, 2023). In 2000, 55 % of the used textiles were exported to the top 10 receiving countries, whereas this number increased to 61 % in 2023. Also, when looking at specific countries, the biggest importers are taking an increasing share, a trend that could also be observed for 2000 - 2019. For instance, Pakistan increased its share from 3 % of the exported used textiles from the EU in 2000 to being the largest importer with 13 % in 2023. Similarly, the United Arab Emirates which was not part of the top 10 in 2000, grew into the second largest importer with 12 % in 2023 (Figure 2.14). This suggests a continued specialisation in these countries.

**Figure 2.14 Extra EU exports of 'worn textiles and clothing' and 'textile rags and scraps', in percentage, by receiving countries, 2023**



**Source**: Comext (Accessed 26.04.2024)

While the largest three importing countries are in Asia, the total imports in volume by African countries are higher. An interesting finding is that the African country Togo is part of the top ten of receiving countries as well, although it is a small country and is therefore unlikely to have a higher demand than neighbouring countries such as Ghana. It might be that Togo acts as an import-re-export hub for the region.

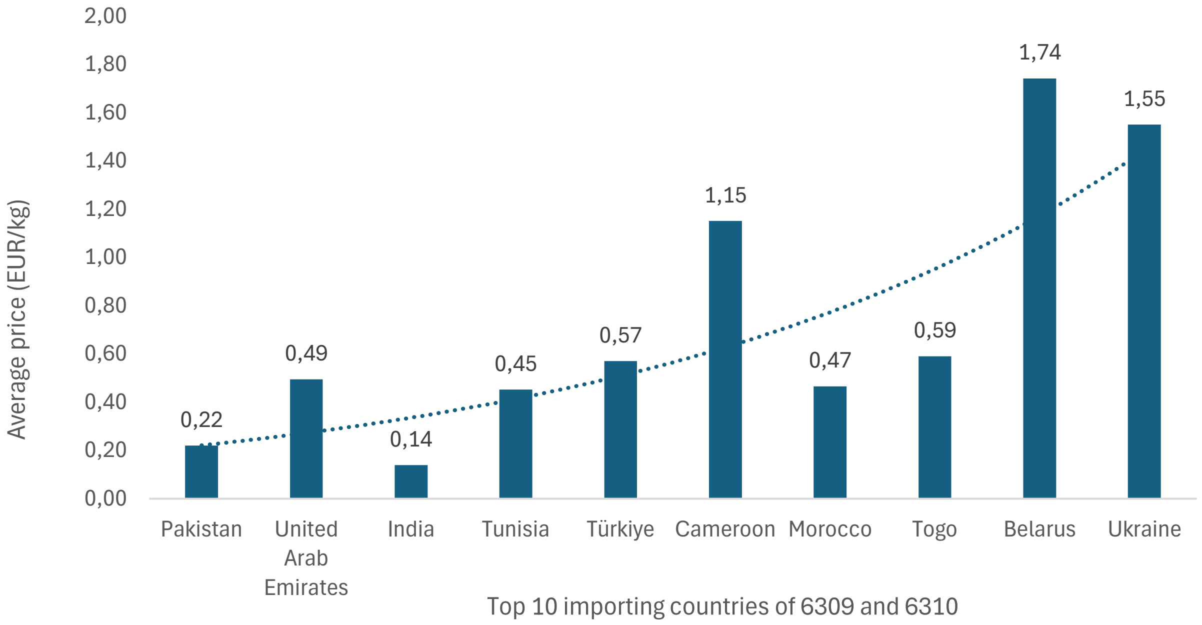
*Prices per kilogram*
Based on the Comext database, it is possible to estimate the price per kilogram of used textiles paid by the top ten importing countries, in current prices. Prices per kilogram are an indicator for the quality of the exported used textiles and their potential fate (reuse or recycling). Price trends for '6309 - *worn textiles and clothing'* and '6310 - *sorted and unsorted used rags and textile scraps'* (combined) show that the average price paid per kilogram of used textiles by the top ten importing countries has decreased over the last decade, from EUR 0.76 in 2000, down to EUR 0.58 in 2010 and EUR 0.57 in 2019 (ETC CE, 2023).

Figure 2.15 shows the price per kilogram that each of the ten biggest importers paid for used textiles (6309 and 6310 combined) to the EU in 2023. The biggest importer, Pakistan, is to the left of the figure, and the smallest importer of the top ten, Ukraine, is to the right.

In 2023, the average price was EUR 0.74 per kilogram, representing an increase in comparison to the 2000 level. However, looking at the different top ten countries, there are large differences. African importers tend to pay more for the used textiles than Asian importers, reaching a price of EUR 1.15 per kilogram for exports to Cameroon, in comparison with EUR 0.14 per kilogram for exports to India. The highest price is paid by non-EU European importer, Belarus, at EUR 1.74 per kilogram.

Figure 2.15 shows an inverse relationship between price and imported quantity. Pakistan, which is the country to which the EU exports the most, pays one of the lowest prices per kilogram, while Ukraine and Belarus, which import the least of the ten biggest importers, pay the highest prices per kilogram. This price difference hints at the different qualities and fates of the exported used textiles, as textiles for reuse are often more expensive than those for recycling. Potentially, the type of textiles exported to Pakistan, the UAE and India are not in condition for actual reuse, and are meant for recycling, while textiles exported to African countries are more likely to be meant for reuse. In that regard, the higher-value reuse items are probably exported to non-EU European countries, such as Belarus and Ukraine.

**Figure 2.15 Average price per kilogram of used textiles for top 10 importing countries, 2023, in current prices (EUR)**



**Source**: Comext (Accessed 26.04.2024).

When only looking at the prices for ‘6309 - *worn textiles and clothing’,* India pays the lowest price per kilogram of the top ten importing countries, suggesting that this fraction in fact is not meant for reuse, which is normally priced higher. This is in line with the fact that India forbids the import of used textiles for reuse, whereas the import of textile scraps is allowed at all ports, and that the importers specialise in re-export, or recycling into wipers, Indian rugs (dhurries) and blankets (ETC/CE, 2023).

## 2.2 Environmental and climate impacts

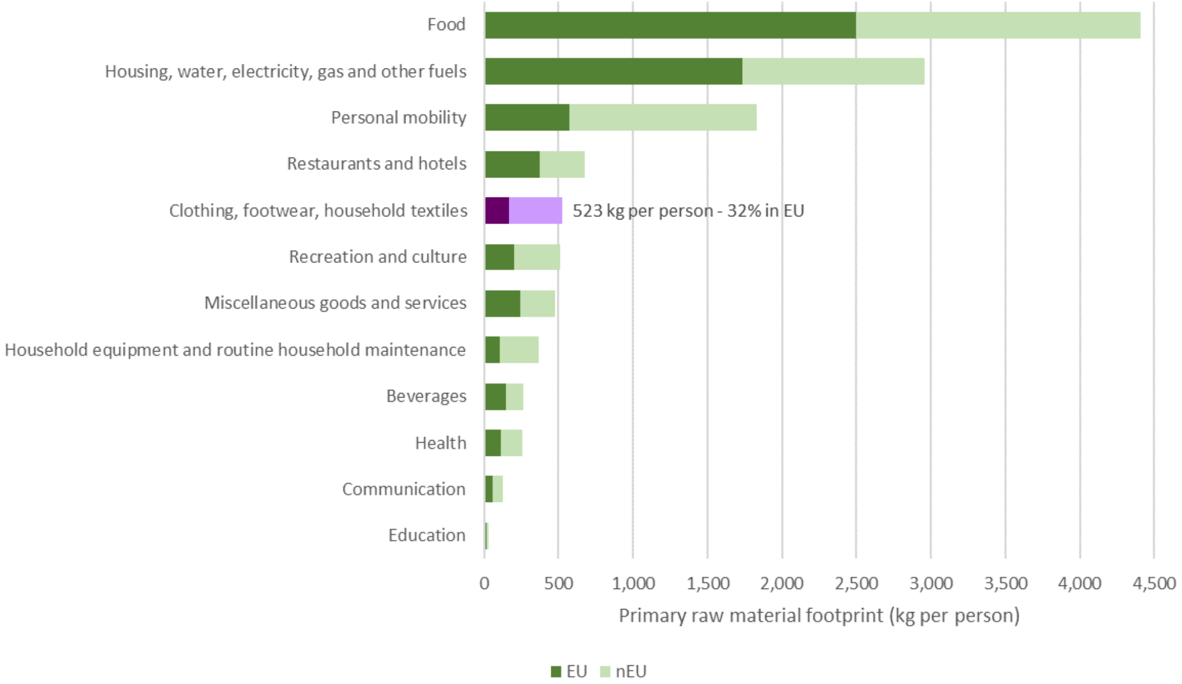
The production and consumption of textiles has significant impacts on the environment and climate change. Like in previous ETC CE reports, these impacts are quantified, focussing on four impact categories to which the textiles value chain is a major contributor, namely raw material use, water use, greenhouse gas emissions and land use.

### Raw material use

To produce all clothing, footwear and household textiles purchased by EU households in 2022, about 234 million tonnes of raw materials were extracted and used (e.g., cotton fibres, natural gas, petroleum), amounting to 523 kg per person (Figure 2.16). This ranks textiles as the fifth highest consumption domain in terms of primary raw material use, after food, housing, mobility, and hotels and restaurants, at roughly the same level as recreation and culture and miscellaneous goods and services. About 32 % of these primary materials are produced or extracted in Europe, which is a relatively low share compared to other consumption domains. Cotton farming, fibre production and garment construction mostly take place in Asia (ETC/WMGE, 2019).

This indicator includes all raw materials extracted or cultivated and used in the upstream production networks of clothing, footwear and household textile purchased by EU households. It does not only include the actual weight of consumed products, but also the material rucksack. The material rucksack represents all raw materials needed in production processes, e.g., for energy purposes and losses.

**Figure 2.16 The use of primary raw materials in the upstream supply chain of EU27 household consumption domains, kg per person, 2022**

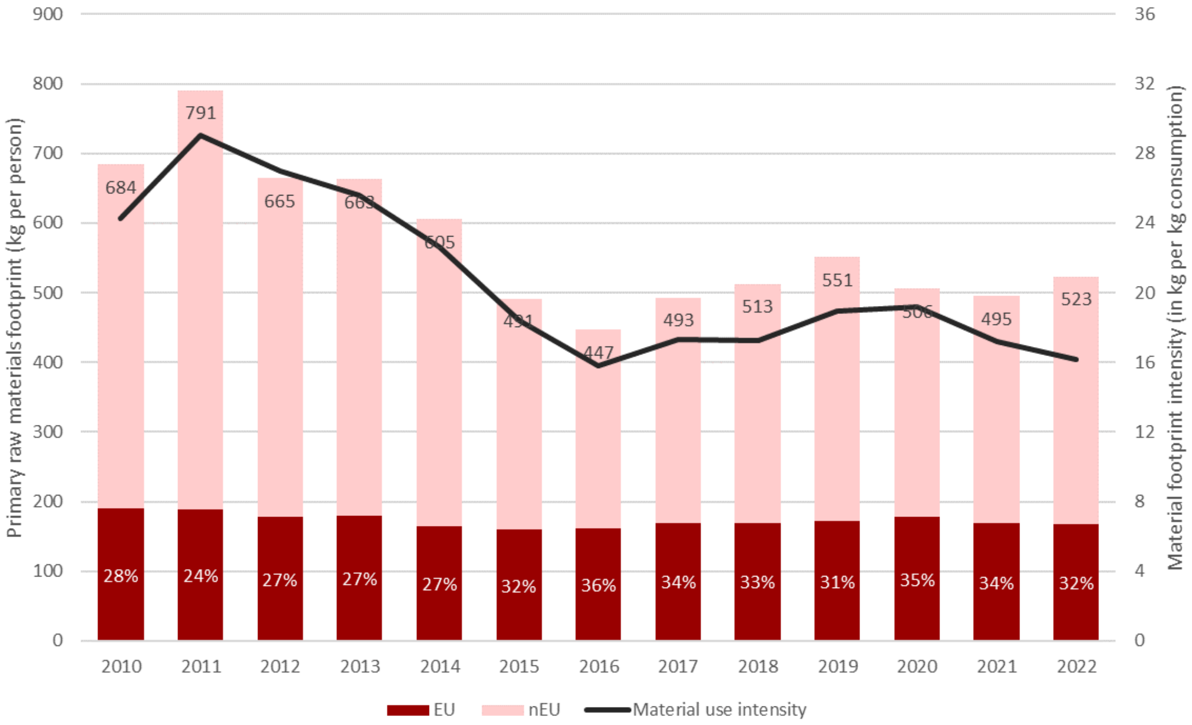


**Source**: ESTAT, FIGARO tables (2024-edition) combined with ESTAT, Air emission accounts by NACE Rev. 2 activity [env_ac_ainah_r2], last update 04/07/2024 and EXBIOASE v3.8.2 to add environmental and social extension data.

Figure 2.17 shows the trend in raw material use for textiles between 2010 and 2022. Notable is the variability on the results, ranging between 447 and 791 kg per person, reflecting some uncertainty linked to this impact indicator. The use of primary raw materials dropped between 2010 and 2016 and has remained relatively stable since. In 2022, a slight increase can be noticed. The share of materials extracted in Europe remains relatively constant at around 30 %.

Comparing raw material use with the total apparent EU consumption of textiles (Figure 2.8, Figure 2.17), a decoupling of impacts can be observed. While consumption volumes per person increased with 15 % between 2010 and 2022, raw material use dropped with 24 % in the same period. These results show that the raw material intensity of textile consumption (i.e., the amount of raw material use per volume of consumption) has decreased considerably (-33 %). Still, in the latest years, these intensity gains seem to have slowed down (Figure 2.17).

**Figure 2.17 The use of primary raw materials in the upstream supply chain of EU27 household consumption domains, kg per person, 2010-2022**



**Source:** ESTAT, FIGARO tables (2024-edition) combined with ESTAT, Air emission accounts by NACE Rev. 2 activity [env_ac_ainah_r2], last update 04/07/2024 and EXBIOASE v3.8.2 to add environmental and social extension data.

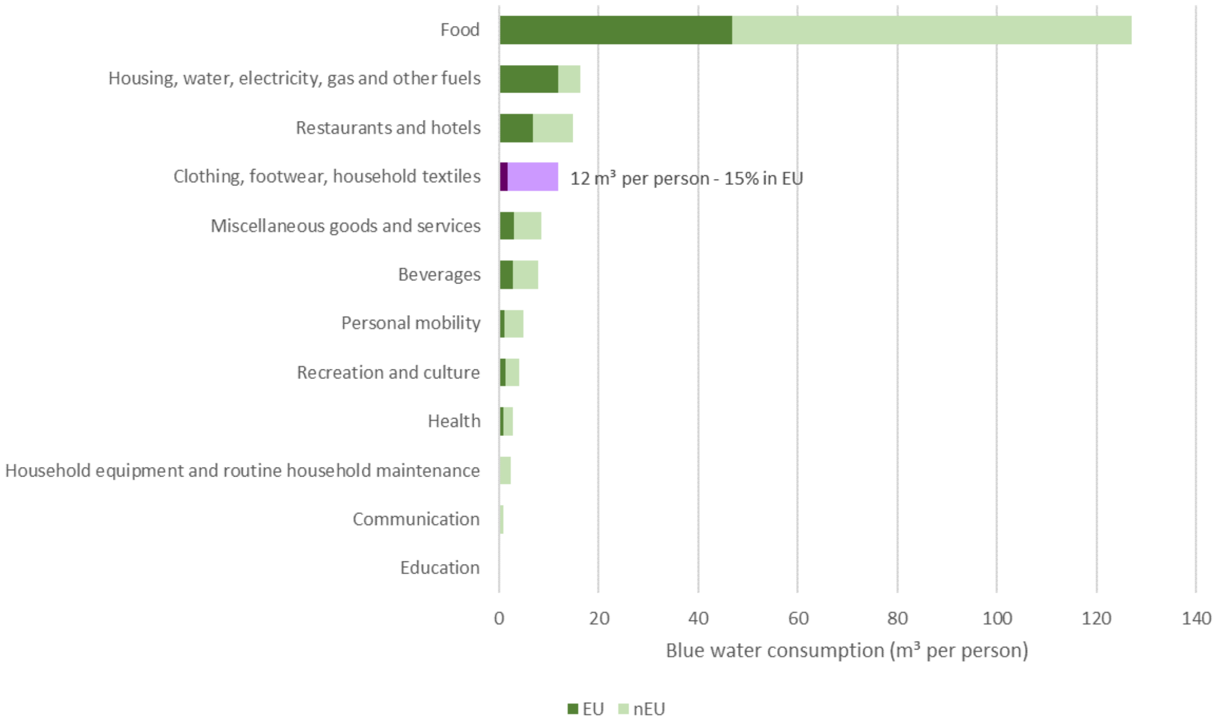
### Water use

To produce all clothing, footwear and household textiles purchased by EU households in 2022, about 5 300 million cubic metres ($m^3$) of 'blue' water[15] were required, amounting to 12 m³ per person, ranking textiles consumption in the fourth place after food, housing, and restaurants and hotels (Figure 2.18). About 85 % of 'blue' water consumption for textiles consumed in Europe takes place outside Europe.

---

[15] When considering water use, a distinction is made between 'blue' water (surface water or groundwater that is consumed or evaporated during irrigation, industry processes or household use) and 'green' water (rainwater stored in the soil, typically used to grow crops) (Hoekstra et al., 2012). In this study, only blue water is considered.

**Figure 2.18 Water use in the upstream supply chain of EU27 household consumption domains, m³ (blue) water per person, 2022**

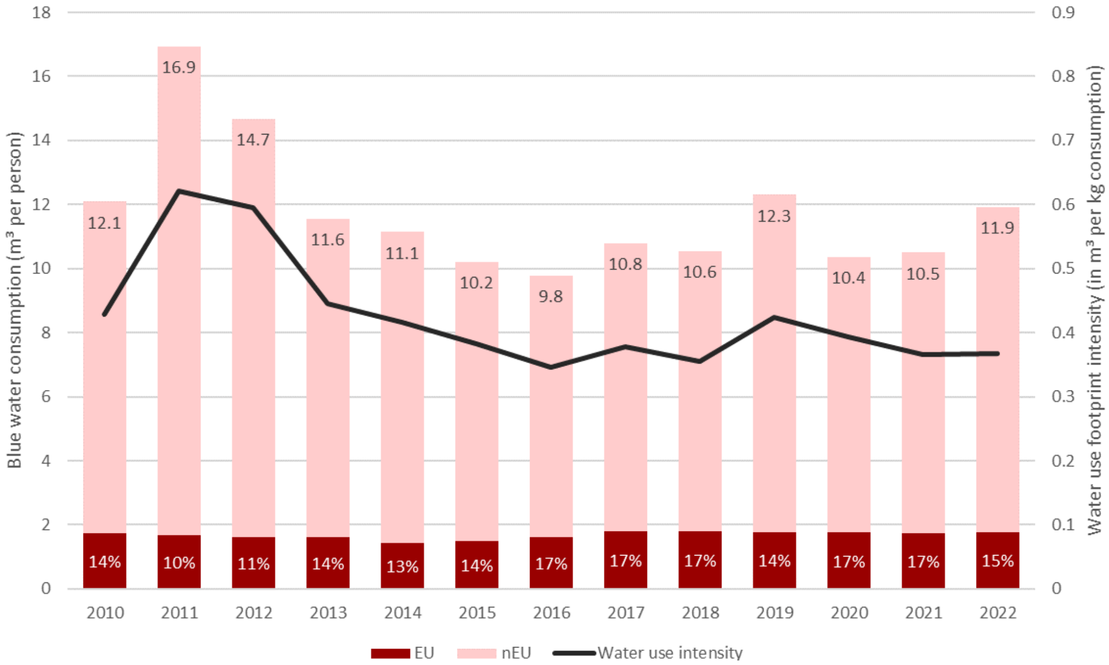


**Source:** ESTAT, FIGARO tables (2024-edition) combined with ESTAT, Air emission accounts by NACE Rev. 2 activity [env_ac_ainah_r2], last update 04/07/2024 and EXBIOASE v3.8.2 to add environmental and social extension data.

Figure 2.20 shows the trend in water use for textiles between 2010 and 2022. Over the years, about 15 % of water consumption is consumed in Europe, while the majority is consumed outside Europe, mainly in Asia where fibre production and textile manufacturing take place.

Comparing water use with the total apparent EU consumption of textiles (Figure 2.8, Figure 2.19), a relative decoupling of impacts can be observed. While consumption per person increased with 15 % between 2010 and 2022, water use remained almost constant (-1 %). These results show that the water intensity of textile consumption (i.e., the amount of water use per volume of consumption) has decreased (-15 %). However, as this decrease in water use intensity is offset by the increased consumption volumes, no absolute decrease in water use per person can be observed, pointing at a relative decoupling.

### Figure 2.20 Water use in the upstream supply chain of EU27 household consumption domains, million m³ (blue) water, 2010- 2022

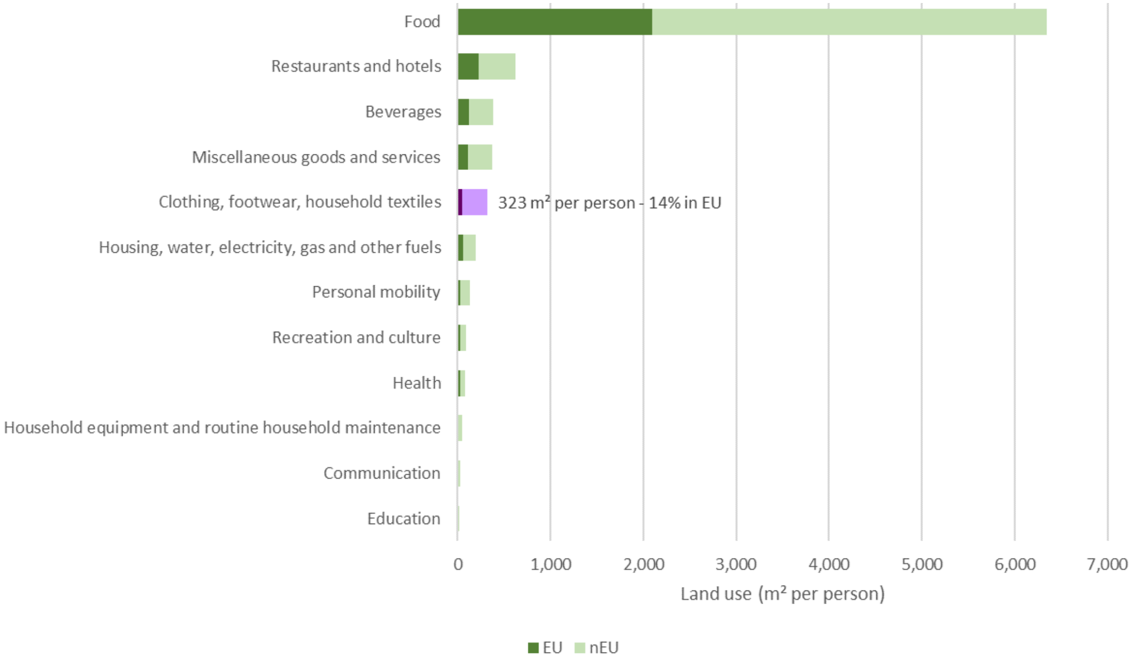


**Source:** ESTAT, FIGARO tables (2024-edition) combined with ESTAT, Air emission accounts by NACE Rev. 2 activity [env_ac_ainah_r2], last update 04/07/2024 and EXBIOASE v3.8.2 to add environmental and social extension data.

## Land use

In 2022, the supply chain of textiles purchased by European households amounted to about 144 000 km², or 323 m² per person (Figure 2.21). Only 14 % of this land use takes place in Europe itself. 86 % of land use impact is generated outside Europe, and can be partly attributed to, for example, cotton fibre production in China and India (ETC/WMGE, 2019).

### Figure 2.21 Land use in the upstream supply chain of EU27 household consumption domains, m² per person, 2022

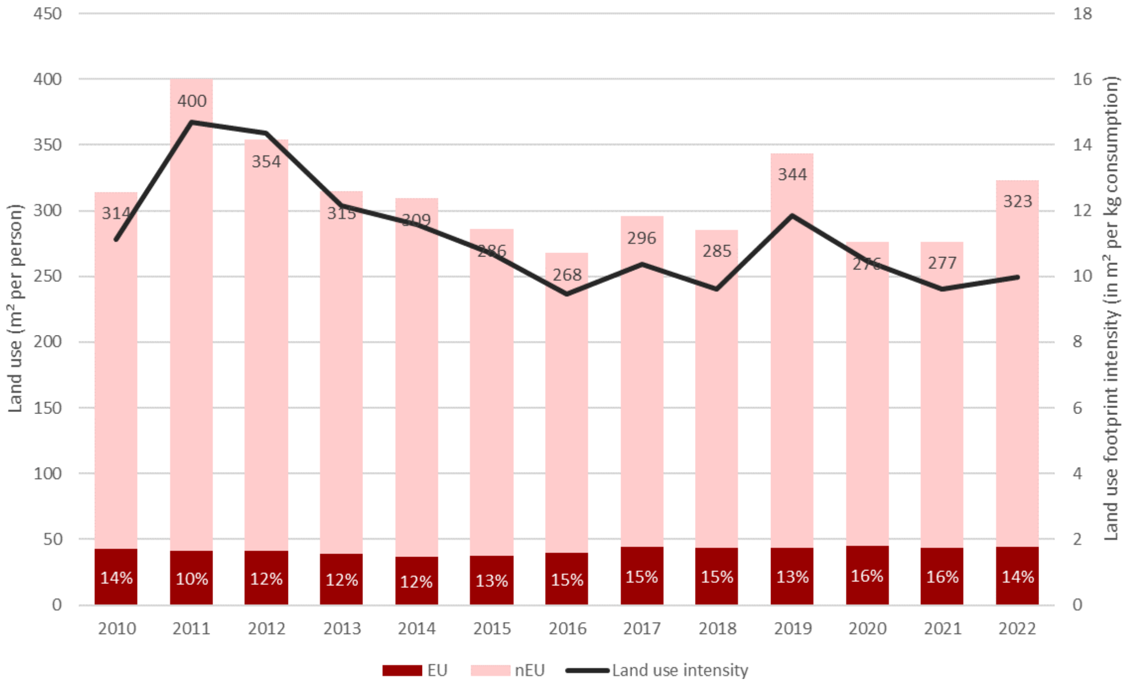


**Source**: ESTAT, FIGARO tables (2024-edition) combined with ESTAT, Air emission accounts by NACE Rev. 2 activity [env_ac_ainah_r2], last update 04/07/2024 and EXBIOASE v3.8.2 to add environmental and social extension data.

Figure 2.22 shows the trend in land use for textiles between 2010 and 2022. The data suggest that after an apparent drop in land use in 2020 and 2021, land use is rising again. European land use for textiles remains relatively constant around 50 m² per person, which represents 15-17 % of total land use.

Comparing land use with the total apparent EU consumption of textiles (Figure 2.8, Figure 2.22), a relative decoupling can be observed. While consumption per person increased with 15 % between 2010 and 2022, land use only increased with 3 %. These results show that the impact on land use of textile consumption (i.e., the amount of land use per volume of consumption) has decreased (-10 %). Still, these intensity gains seem to have slowed down in recent years.

**Figure 2.22 Land use in the upstream supply chain of EU27 household consumption domains, m² per person, 2010-2022**

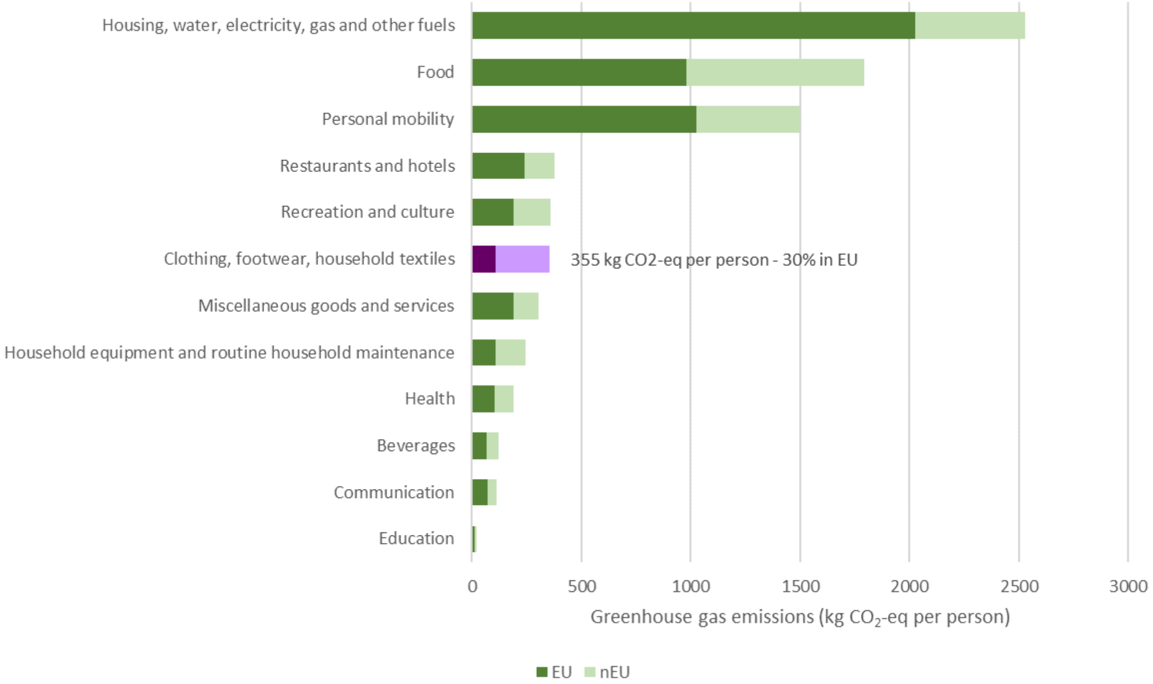


**Source:** ESTAT, FIGARO tables (2024-edition) combined with ESTAT, Air emission accounts by NACE Rev. 2 activity [env_ac_ainah_r2], last update 04/07/2024 and EXBIOASE v3.8.2 to add environmental and social extension data.

### Greenhouse gas emissions

In 2022, the production of textile products consumed in the EU generated total greenhouse gas emissions of 159 million tonnes of $CO_2$-eq in total, corresponding to 355 kg $CO_2$-eq. per person. This makes textiles responsible for the sixth largest climate impact among household consumption domains, after housing, food and mobility (Figure 2.23 Greenhouse gas emissions in the upstream supply chain of EU27 household consumption domains, million tonnes CO2eq. per person, 2022), and comparable to restaurants and hotels, and recreation and culture. About 70 % of emissions are released outside Europe, in textile-producing regions in Asia (ETC/WMGE, 2019).

**Figure 2.23 Greenhouse gas emissions in the upstream supply chain of EU27 household consumption domains, million tonnes CO2eq. per person, 2022**

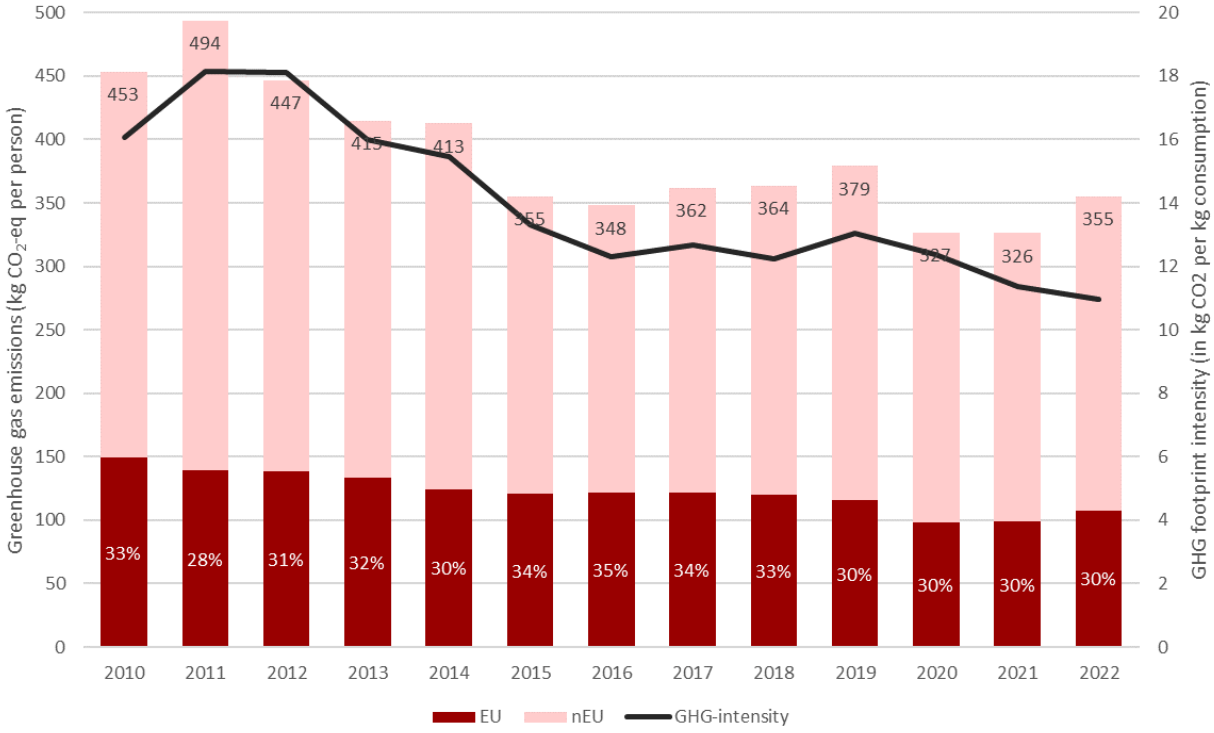


**Source:** ESTAT, FIGARO tables (2024-edition) combined with ESTAT, Air emission accounts by NACE Rev. 2 activity [env_ac_ainah_r2], last update 04/07/2024 and EXBIOASE v3.8.2 to add environmental and social extension data.

Figure 2.24 shows the trend in greenhouse gas emissions for textiles between 2010 and 2022. An overall decrease in greenhouse gas emissions can be observed over this period, with an overall low in 2020 and 2021 due to reduced consumption during the COVID-19 crisis. However, for 2022 again a slight increase in emissions can be observed. About 70 % of greenhouse gas emissions take place outside Europe, in the manufacturing regions, a figure that has not changed much over the past decade.

Comparing greenhouse gas emissions with the total apparent EU consumption of textiles (Figure 2.8, Figure 2.24), an absolute decoupling can be observed. While consumption per person increased with 15 % between 2010 and 2022, greenhouse gas emissions decreased with 22 %. This shows a decreasing greenhouse gas emission intensity of textile consumption (i.e., the amount of emissions per volume of consumption) has decreased (-32 %), resulting in an absolute decoupling.

**Figure 2.24 Greenhouse gas emissions in the upstream supply chain of EU27 household consumption domains, million tonnes CO2eq., 2010-2022**



**Source:** ESTAT, FIGARO tables (2024-edition) combined with ESTAT, Air emission accounts by NACE Rev. 2 activity [env_ac_ainah_r2], last update 04/07/2024 and EXBIOASE v3.8.2 to add environmental and social extension data.

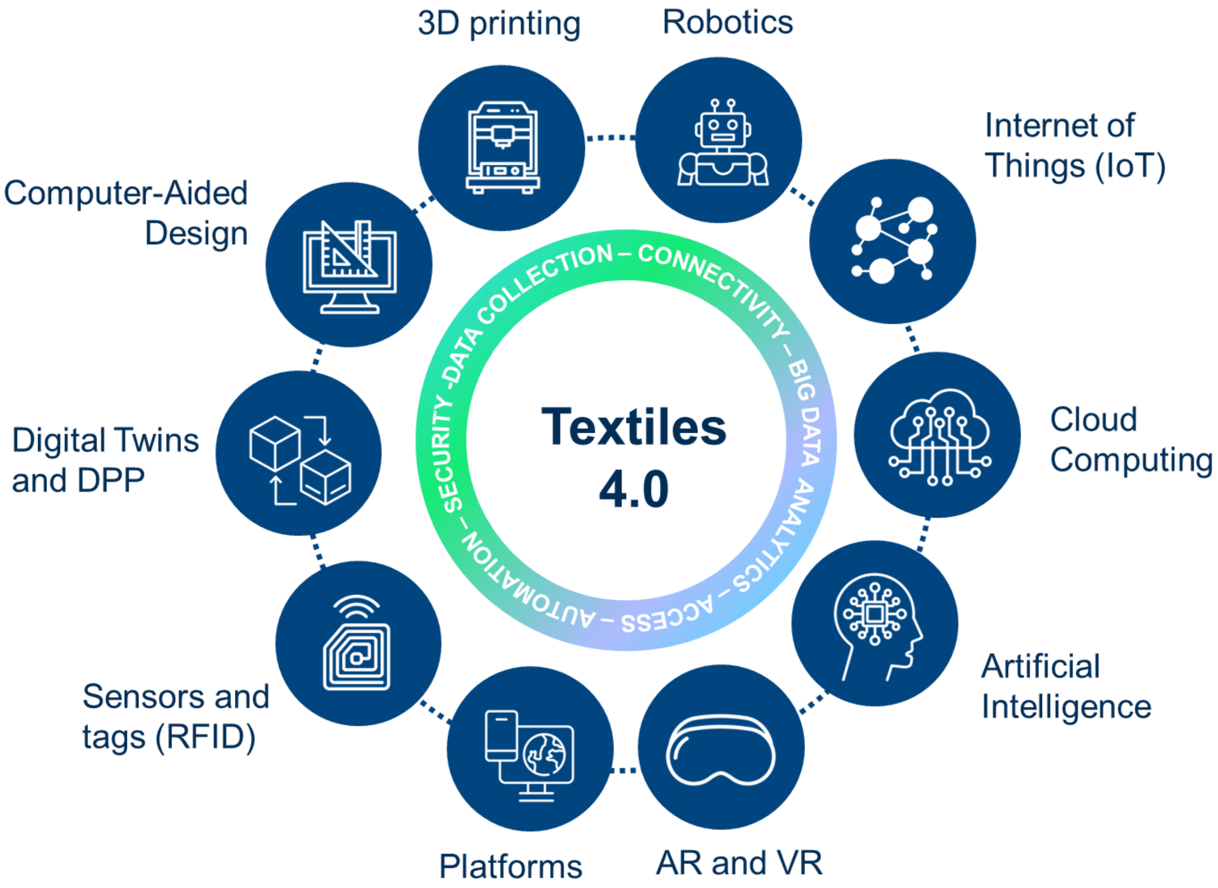
# 3. Textiles 4.0: Digital solutions for sustainability and circularity of textiles

## 3.1 Introduction to Textiles 4.0

Industry 4.0, often referred to as the Fourth Industrial Revolution, involves the integration of advanced digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and automation into traditional manufacturing processes and all areas of business.

In the textile industry, a plethora of digital technologies are emerging (Figure 3.1 and Annex 3), bringing several transformative changes to the industry, its employees and its customers, potentially making it more efficient, productive, and responsive to market changes and customer demands (Broccardo et al., 2023). In addition, digital technologies are often mentioned to be a crucial enabler to make the textiles system more resource-efficient and transparent, supporting innovative design approaches, smart production processes, better matching supply-demand, optimisation of supply chains using real-time data, waste reduction, new business models and improved product lifecycle management (Kristoffersen et al., 2020; Chauhan et al., 2022; Rantala et al., 2023; Antikainen et al., 2018). Also the EU Strategy for Sustainable and Circular Textiles acknowledges the digital transition to be a potential key enabler to achieve resilience and sustainability in the industry (European Commission, 2022).

**Figure 3.1 Digital technologies emerging in the textiles industry**



**Source**: VITO

While many researchers and practitioners tend to have a generally positive view on the merits a digital transformation could bring (Trittin-Ulbrich et al., 2021), a nuanced view on possible trade-offs, limitations, and risks and a thorough discussion about how it contributes to sustainability of textiles is indispensable (Broccardo et al., 2023). On the one hand, technology can enhance product design, improve production processes, facilitate communication with the consumer, e.g. by better conveying sustainability information and influencing sustainable purchases, and streamline end-of-life management. Points of attention that are mentioned in literature are the energy and water use needed to run and cool datacentres and support AI (IEA, 2024; Li et al., 2023); the risk of efficiency gains resulting in increased consumption (i.e. Jevons' paradox), a (potentially unintended) lowering of product quality (Martinez-Jaramillo and Tilebein, 2024) and neglecting environmental and social performance (Broccardo et al., 2023). Overconsumption – a major pain point in the textiles system, will not be solved by technology alone, making behavioural change, as well as regulation indispensable to assure sustainability *[interview].* Moreover, since several digital technologies are used for tracking of customer needs and interests, targeted marketing and driving of demand, they could even fuel increased consumption.

Since the 2000s, the adoption of e-commerce and online platforms has become increasingly common (Izsak and Moreno, 2024). As in many industries, the COVID-19 pandemic has accelerated the textiles industry's digital transformation. Previously, many retailers primarily relied on physical stores, but mandatory closures during the pandemic pushed them to establish e-commerce websites [*interview*]. This acted as a driver for consumers to experiment with new digital methods for accessing products and services, such as online and mobile shopping (PricewaterhouseCoopers, 2020).

Further upstream in the supply chain, the lack of physical textile fairs led to an uptake of digital design and prototyping, and increased digitization of fabrics. Encouraged by digital developments, many companies have taken up digital tools to maximise resources and reduce waste in production and manufacturing, for example digital printing. Moreover, large, international players, as well as niche companies have built their business model around digitization [*interview*]. An increasing number of digital textile tech startups are leveraging AI, AR/VR, and blockchain to offer innovative services, create new revenue streams, and drive differentiation. By integrating multiple digital technologies, these startups are reshaping value propositions within the textile industry (Izsak and Moreno, 2024). However, despite increasing industry interest, digital technology adoption in the textiles and fashion industry has been slow, especially among SMEs, due to barriers such as financial constraints, lack of expertise, and resistance to change (Casciani et al., 2022; Izsak and Moreno, 2024). Moreover, digital technologies are rarely adopted for the reason of sustainability or circularity alone. Instead, the predominant reason for their introduction is efficiency rather than sustainability *[interviews]*. At the same time, digital tools can be an important enabler for compliance with (upcoming) EU regulations and hence may help to advance sustainability ambitions.

The remainder of this chapter is built up as follows. Section 3.2 presents a detailed overview of the use of different digital technologies in different phases of the value chain. Section 3.3 explores the role of digital technologies as enablers of circular business models. Finally, section 3.4 looks at implementation barriers companies face when trying to adopt digital technologies. An extensive glossary of the main digital technologies discussed in this report and their application in the textiles industry can be found in Annex 3.

## 3.2 The use of digital technologies throughout the textiles value chain

Digital technologies offer some key functionalities that hold potential for contributing to the circular economy (Böttcher et al., 2023; Bressanelli et al., 2018). From an environmental angle, digital technologies can contribute to extending the life of clothing (*slowing loops*), reducing raw material consumption, improving resource efficiency and reducing waste in textile production and use (*narrowing loops*), and facilitating reverse flows and high-quality textiles recycling (*closing loops*) (Bocken et al., 2016). From an economic dimension, cost reductions can be achieved by saving or sharing resources, reuse, and recycling. Additionally, new or increased cash flows can be generated by developing new business models and value propositions. In view of social sustainability, digital tools make it easier to involve stakeholders in the creation and improvement of sustainable business models, by for example, enabling community building, involving local authorities, better customer need assessment, and the democratization of entrepreneurship (Broccardo et al., 2023).

On the other hand, the surge of digital technologies in the textiles system can also have environmental and socio-economical downsides, including increased energy use from data processing, the risk of even more consumption due to faster production cycles and loss of jobs in production and retail.

In the following paragraphs, the use of digital technologies in the different stages of the textiles value chain is mapped, presenting the current state-of-the-art, emerging digital technologies that are expected to gain importance in the near future and their associated opportunities, challenges and risks in relation to supporting the transition to a sustainable and circular textiles system.

### Product design

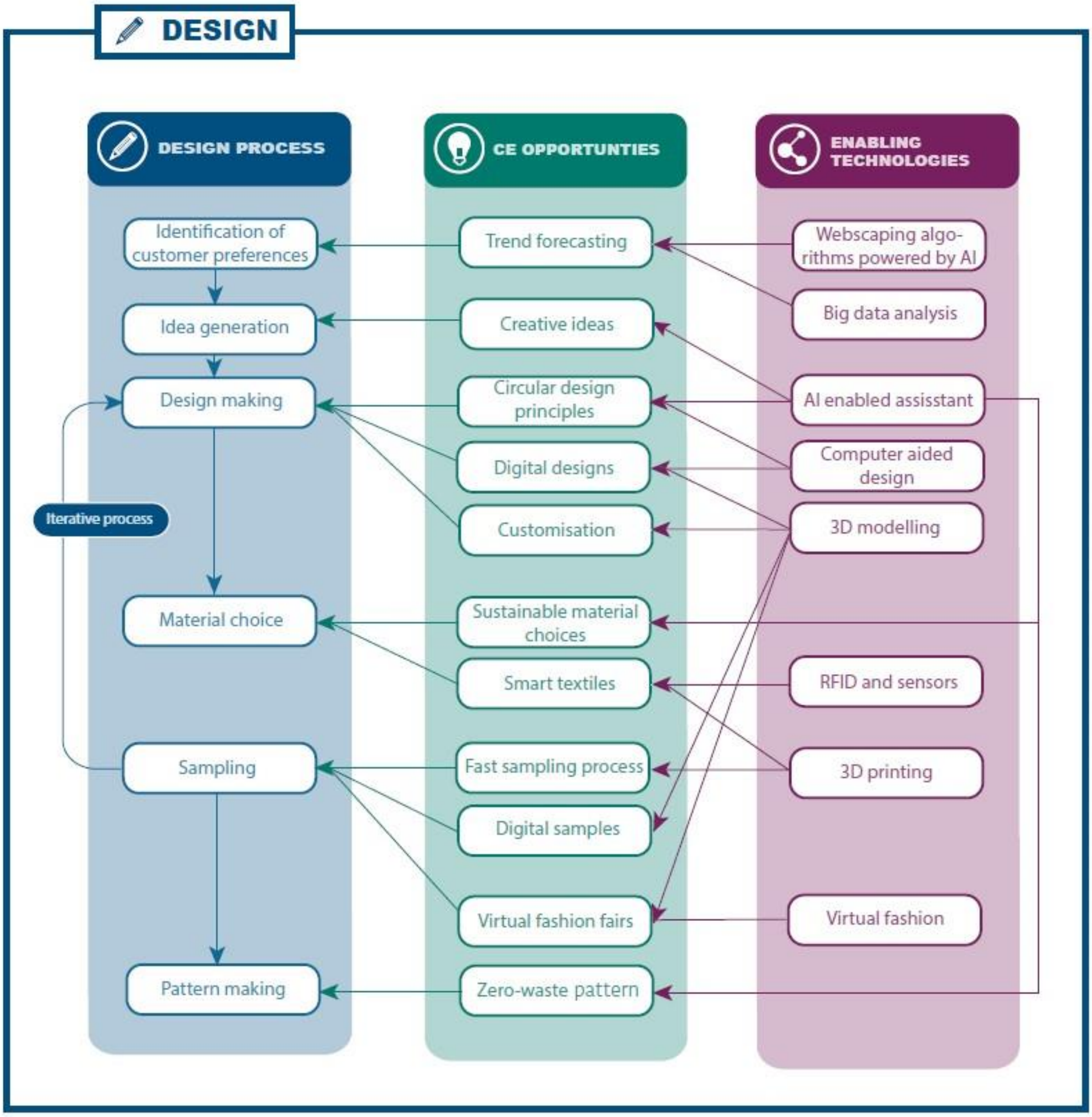
Digital technologies offer many potential benefits during the product design stage (Figure 3.2)**.** The process of product conception, design and engineering is a very iterative process, which traditionally involves a lot of manual work and sampling to test and evaluate the designs and present them to potential buyers. Especially the creation of physical samples is a costly, time-consuming and wasteful process, since those samples are usually not used or sold, but get destroyed (ETC/CE, 2024b). Moreover, the global nature of textiles business and trade implies that these samples are sent around the world between designers, producers and customers, or to fashion fairs, creating a huge logistic burden [*interview*].

Already today, several steps in the design process have undergone digital transformations to varying extents. Digital technologies, such as computer-aided design (CAD), 3D modelling and 3D printing, have shifted the design and sampling process towards the digital realm. This can speed-up the iterative design process significantly, enhances cross-department collaboration between designers, stylists, and pattern makers, and reduces resource use by enabling detailed digital visualizations without the need for physical samples and associated logistics (Casciani et al., 2022). Additionally, customization allows products to be personalized to fit any body shape using technologies like 3D body scanning, eliminating traditional sizing constraints, thus promoting inclusive design approaches (Wiegand and Wynn, 2023; Casciani et al., 2022).

Some manufacturers estimate a time saving of 50 % and significant savings in materials and patterns (KPMG, 2021). Several businesses interviewed in the frame of this study confirmed that the use of digital design tools and prototyping shortens production and planning times and generates less waste, as they allow for a better analysis and reusability of designs in other colours and patterns, better optimisation and lower error margins. It could even be coupled to software that estimates environmental impact [*interviews*]. One of the interviewees, active in production and retail, stated that they were able to reduce the number of physical samples by 60 % *[interview].*

Digital collections, online catalogues, interactive, virtual shows, and immersive environments can even replace the resource-consuming fashion fairs and deliver large savings in B2B prototype and wholesale logistics [*interview*]. Some studies estimated that a 30 % - 97 % reduction in carbon footprint could be achieved by shifting from physical to digital fashion sampling, as well as saving considerable volumes of water. However, these studies did not include the impact of energy-consumption related to digital storage and datacentres (Casciani et al., 2022). However, care must be taken regarding the actual effects. A study found that the environmental effects of the first completely digital fashion week held in Helsinki in the Fall-Winter 2020 season had a higher overall carbon footprint than that of traditional fashion shows, but lower if calculated per visitor (Casciani et al., 2022).

**Figure 3.2 Use of digital technologies in the design stage of textiles**



**Source:** VITO/CSCP/ETC-CE

Despite the emerging of these digital solutions physical samples are still common, due to some technological and cultural barriers. First, many digital technologies are not performing sufficiently well yet. Interviewees stated that simulating physical properties of fabrics and their behaviours in a realistic way is very difficult and still not perfect, such as fabric touch and feel, drape, or simulating colour as this depends heavily on light conditions etc. *[interviews].* Further developments in creation of more realistic digital fabrics, with accurate colour and draping properties, are needed, to make real-time simulations more precise and realistic and overcome the barriers that still hamper the full transition from physical to digital sampling (Arillo García, 2023). There is also cultural hesitance since most people - designers, producers, purchasers as well as consumers – want to see and touch the product, or see it worn by a real person before making a decision *[interviews]*. The third reason is a matter of skills. Digital skills are often lacking at all levels in the textiles industry.

It is expected that more digitalization will happen in the design process in the coming years, especially in prototyping *[interview]*. Two of the interviewees confirmed that the COVID-19 pandemic forced textile manufacturers to explore alternative means to showcase fabric collections, as there were no physical fairs and limited logistic options to send around samples. This led to increased investments in and improved uptake of virtual prototyping solutions and 3D-simulation of garments *[interviews].*

As in many fields, the use of artificial intelligence (AI) is also emerging in fashion and other textiles design. While there are some concerns and uncertainties about AI replacing human creativity, some experts believe that AI will mainly serve as a technical and creative assistant to a knowledgeable human operator. Collaborative human-AI design offers potential, for example, to increase designers' creativity and productivity, offering support to create designs faster, with a better fit or better match with requirements, create variations on existing designs, etc. while also using data and analytics to understand and better predict consumer preferences (Arillo García, 2023).

In terms of sustainability, AI algorithms could be used, for instance, to help designers with making material choices, optimizing for sustainability performance and taking into account circularity parameters (EURATEX, 2023b). Furthermore, by integrating AI algorithms into the pattern making process, the concepts of 'zero-waste design' and 'zero-waste pattern cutting' can be introduced, aiming to create patterns and pattern piece arrangements that optimize fabric utilization and reduce cutting waste (Gür, 2023; Casciani et al., 2022). However, such AI-based expert systems for sustainable design are still emerging, and further R&D, piloting and user training is still needed (EURATEX, 2023b) *[interview]*.

Nonetheless there are also valid concerns and risks related to the use of AI in design, such as the extensive energy demand related to the use of AI algorithms ((UN digital economy report 2024). Also, increased efficiency can come with a downside if it leads to cheaper products and increased consumption (Jevon's paradox) or faster-changing fashion trends. Also, when time-to-market times reduce due to faster digital design and automated production processes, there is a significant risk that digital technologies will act as an accelerator of fashion trends, further fuelling (ultra-) fast fashion and inflating consumers' needs and desires to refresh their wardrobes in response to social media.

Innovation in textile technology opens up the opportunities of smart textiles with enhanced functionality due to integrated sensors. Some recent developments within the field of 'smart textiles' include e-textiles containing electronic components (e.g. RFID tags) or sensors, thermal regulation textiles, e-skin for tactile sensing and much more (Keefe et al., 2022). Smart textiles can regulate temperature or collect data for medical or sport purposes (e.g. smart sneakers), or change colour (KPMG, 2021). When integrating smart textiles with an IoT system, clothes can be used as communication tools, e.g. to discreetly and continuously monitor the health of wearers and transmit those data to healthcare professionals (Keefe et al., 2022). The production of these smart textiles often employs additive manufacturing techniques to connect or build electronic sensors, such as wearable RFID antennas to the textile fabric, a process which is sometimes referred to as '4D printing' (Keefe et al., 2022). In the case of smart textiles, some concerns arise related to their recyclability and end of life treatment, due to their complex composition, e.g. the presence of electronic components in a textiles waste stream (Köhler et al., 2011).

A very recent development in digital fashion design is the trend of virtual fashion. Virtual clothing exists only in the virtual space – the "metaverse"-, combining the development of digital design and virtual or augmented reality functionalities (VR and AR) with social media and video games. Virtual fashion can take the form of avatar skins, digital-only clothes used as a photo-overlay or AR clothing for use in real-time in an AR mirror, combining virtual and physical realities (Boston Consulting Group, 2022). Typically virtual fashion items are provided in the form of non-fungible tokens (NFTs) that are individual, unchangeable and cannot be copied, only be passed on through a decentralized database system (KPMG, 2021). With virtual fashion, nothing limits a designer's creativity. Important target groups for virtual fashion are online influencers that can “wear” these clothes in photos and videos, and gamers that buy personalized outfits or ‘skins’ for their avatars. Dressing up digital avatars is no longer just a game, but a way to express ones identity and creativity, and it represents a huge economy (Arillo García, 2023). From that perspective, virtual fashion meets fashion’s social functions, including self-expression, identity statement, and communication through social media (Casciani et al., 2022) [*interviews*].

Although the trend of virtual fashion is very recent, an analysis by Boston Consulting Group (2022) reveals that about one-third of the world’s 120 leading fashion companies have already experimented with the metaverse. It is expected that most leading companies will have engaged with it by 2030. While the concept may seem abstract to the general public, consumers increasingly value their digital presence, particularly in Asia, where 45% of digital users consider their digital appearance as important as their physical appearance (Boston Consulting Group, 2022). A survey by KPMG showed that virtual fashion is especially gaining popularity with media-savvy groups between the ages of 18-44 (KPMG, 2021).

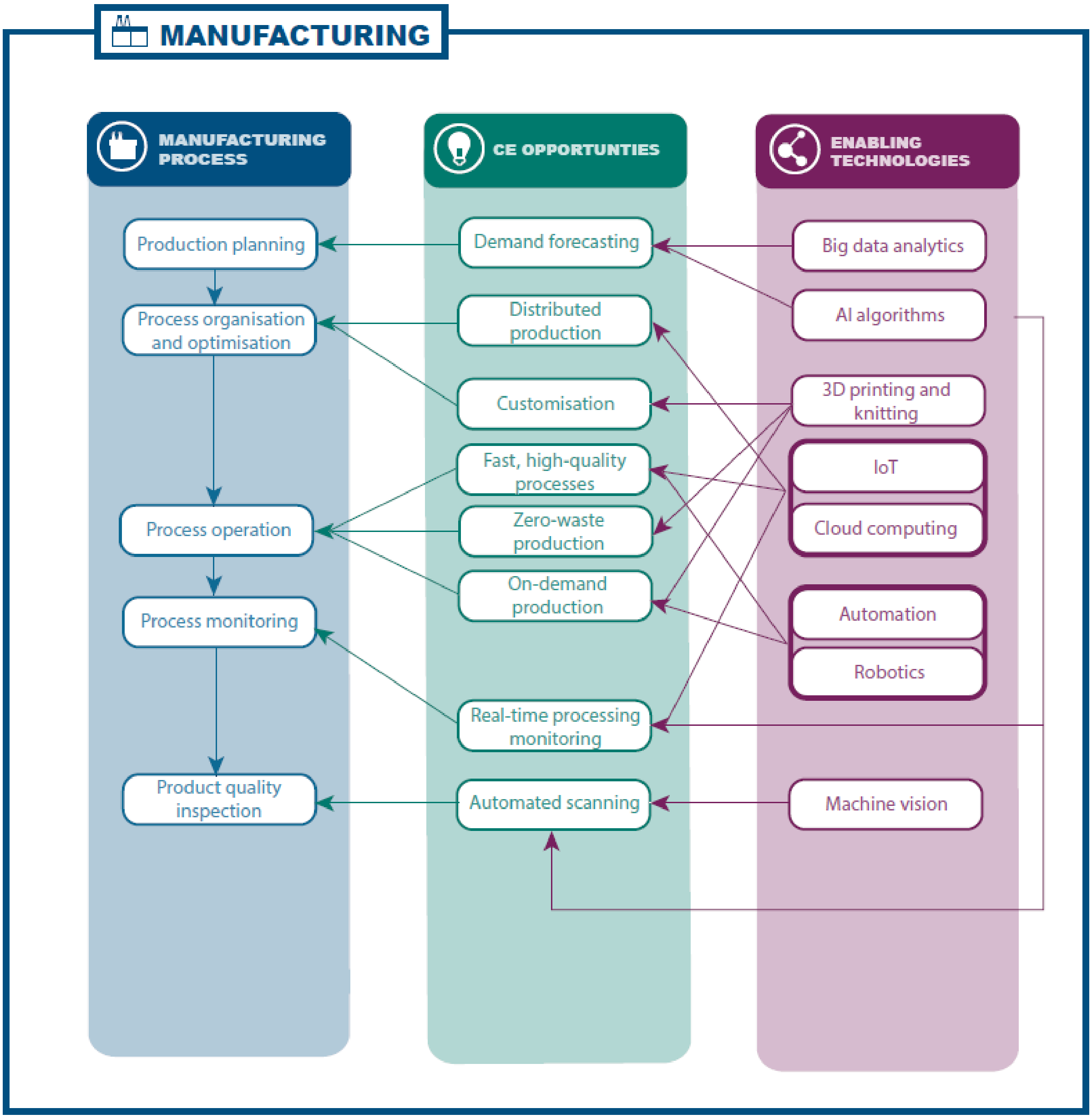
While some point to the substantial environmental and climate impact related to virtual fashion, others believe that digital fashion could be a disruptive force enabling the fashion industry to become more sustainable. On the one hand, virtual fashion requires no physical production or material investment and does not generate tangible waste, while on the other hand, metaverse and blockchain technologies consume considerable amounts of energy. However, while as digital fashion mainly serves as a powerful complementary force to traditional physical fashion, it is unlikely to fully replace it, implying impact savings from avoided physical production might be limited (Arillo García, 2023). In addition, digital fashion also replicates fast consumption behaviours in the digital realm, and digital garment consumption also has a carbon footprint due to energy consumption (Casciani et al., 2022). Boston Consulting Group calculated several impact scenarios, estimating the rise of digital fashion could increase fashion industry carbon emissions with 0.1 to 1.2% by 2030 (Boston Consulting Group, 2022). To make digital fashion a “force-for-good”, it should lead to a partial replacement of physical fashion, reducing overproduction and material use**.** Therefore, as fashion is entering the metaverse, it is vital to incorporate sustainability mechanisms from the start before it faces exponential growth that could rapidly scale up environmental costs: conscious technology choices, set sustainability standards for the metaverse and awareness raising of the impact of digital purchases.

### Textile manufacturing

Digital technology can do a lot to make traditional textile production smarter and more efficient and to reduce waste (Antikainen et al., 2018) (Figure 3.3). A lot of inefficiencies during manufacturing lead to pre-consumer waste. For example, poor insight in customer demand leads to overproduction of items that remain unsold and need to be destroyed (ETC/CE, 2024b) [interview], poor process control and insufficient quality monitoring leads to faulty products and waste. It is estimated that 8% of yarns, 13% of fabrics and 20% of finished textiles in the EU may be lost during manufacturing (Huygens et al., 2023). Digital technologies can help streamline the production process.

In manufacturing, sensors and IoT can be used to operate, organise and monitor production machines using real-time data monitoring. This way, production planning can be improved, energy and resource use of factories can be reduced, supply chains can be better aligned and products can be tracked throughout their productions process (Casciani et al., 2022; Rantala et al., 2023). Quality control operations, which nowadays are often still a manual process, can also be streamlined using digital solutions. For example, there are digital solutions that allow online control of machine operations, process quality control and quality inspection of the final products. These systems automatically scan the fabrics, feed the images into an AI algorithm able to identify defects and decide whether the product fits quality standards or not, and whether machines need to be stopped or adjusted *[interview]*.

Figure 3.3 Use of digital technologies in the manufacturing stage of textiles



**Source:** VITO/CSCP/ETC-CE

In the distributed production model of the textiles sector, combining IoT with cloud computing allows creating networks of manufacturing plants, which can be operated, optimised and monitored from anywhere in the world, resulting in more efficient production, cost reductions, better traceability of production steps, shorter lead times and economies of scale (Ahmad et al., 2020), although also some risk may be associated with the creation of such networks *[interview]*.

By incorporating automation and robotics into production processes, companies can enhance productivity, minimize waste, and improve quality by eliminating human errors. Efficient cutting and sewing technologies, such as automated cutting machines and computerized sewing systems, ensure precise material usage, reducing fabric waste, as well as production mistakes [*interview*]. For instance, robots designed for fabric stacking can accurately position all parts of the upper part of a sneaker shoe in 50 to 75 seconds, a task that would take a human worker over ten minutes. While concerns are to be raised on how the implementation of robotics negatively affects employment (especially of women), it might also reduce the labour intensity of the process, thereby decreasing the reliance on and potential exploitation of low-wage workers in developing countries (PricewaterhouseCoopers, 2020).

Automation can also significantly reduce lead times. As clothing production takes time, production currently takes place 6, 9, or 12 months ahead of the actual moment when the product is being sold, which means that there is a lot of misjudgement of demand, leading to overproduction, markdowns and unsold items that need to be destroyed (ETC/CE, 2024b) [*interview*].

Moreover, robotics and automation could possibly bring a real on-demand fashion production system into existence in the future, with new business models putting consumers in the lead of what is produced [*interview*]. On-demand production systems enable brands to manufacture items faster and only when there is confirmed demand, cutting down on excess inventory and associated resource wastage. However, as stated earlier there is also a potential downside to these reduced lead times, as they might result in even more overproduction and -consumption.

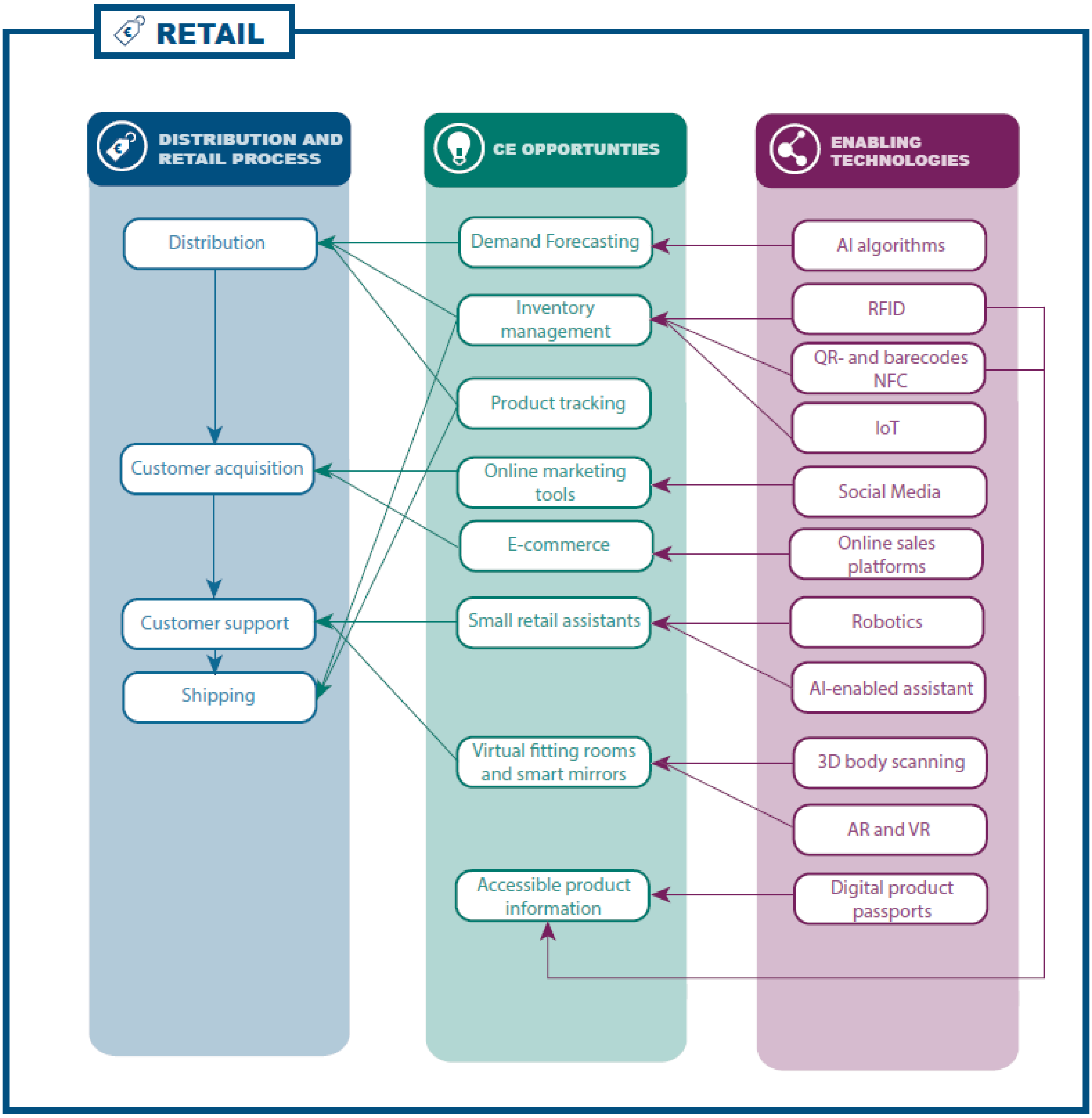
New production technologies based on the principle of additive manufacturing such as 3D printing or 3D knitting, are rapidly emerging within the textiles industry. They not only allow fast, customised and zero-waste production (Wiegand and Wynn, 2023; Bressanelli et al., 2018), but also facilitate the manufacturing of complex products that are not easily produced using traditional manufacturing methods. After deciding, the customer can order a physical garment that is instantly produced on-site by a 3D printer or knitter. This approach saves time and eliminates shipping costs, as well as the environmental impact associated with the traditional supply chain (Keefe et al., 2022; PricewaterhouseCoopers, 2020). It can reduce or eliminate the need for stocks, avoid overproduction of items nobody wants and holds opportunities for reshoring of garment production on a local scale, eliminating long-distance transports of materials and employing local labour (Casciani et al., 2022) [*interviews*].

### Retail and customer interactions

Digital technologies are revolutionizing retail by enhancing customer experience and streamlining operations (Figure 3.4).

E-commerce through online sales platforms has greatly increased since COVID-19 (ETC/CE, 2024a). Moreover, there are new digital technologies emerging that can bring shopping experiences to a new level for consumers and allow for direct, so-called ‘D2C’ (Direct-to-Consumer) marketing in which intermediaries are eliminated as consumers purchase directly from brands (Casciani et al., 2022). However, since D2C-parcels are often directly shipped by economic operators outside the EU, lack of transparency and customs control can result in a high risk of non-compliance of the shipped products with EU legislation, for example related to health, safety or the presence of chemicals of concern (Cobbing et al., 2024; Le Monde, 2024). Security solutions for digital platforms offer smooth and sure transactions, such as  reservation, payment, user identification etc. (Rantala et al., 2023). Overall, these digital advancements have the potential to transform fashion retail, making it more efficient and customer-centric. On the other hand, e-commerce also brings some negative implications for environmental sustainability, related to how businesses handle warehousing, storage, transportation, logistics, packaging and returns, as well as to consumer behaviour (such as impulse buying) in response of the enhanced accessibility, convenience and greater variety that e-commerce offers (United Nations Conference on Trade and Development (UNCTAD), 2024), as well as the potentially addictive design of e-commerce platforms (European Commission, 2024b). Despite these perceived advantages for consumers, recent data rather shows that they are returning to in-store shopping at pre-pandemic levels (McKinsey & Company and BOF Insights, 2024).

Figure 3.4 Use of digital technologies in customer interaction and retail of textiles



**Source:** VITO/CSCP/ETC-CE

Advanced tools such as augmented reality (AR) and virtual reality (VR), optionally combined with a 3D body scanning device, allow customers to virtually try on clothes, providing a personalized and immersive shopping experience without the need to physically try on garments. In e-commerce, this could potentially avoid returns. Virtual dressing rooms or smart mirrors can also act as smart assistants in physical shops, especially when goods can be easily identified using RFID technology (KPMG, 2021). Some brands have already developed virtual fitting rooms on SnapChat and Instagram, using AR technology to 'try on' make-up, (sun)glasses, jewellery, shoes and bags (PricewaterhouseCoopers, 2020). In the case of tailor-made clothing, 3D scanning could be used to provide the tailor with the exact measurements of the customer, which is particularly useful for online repair services through which the customer and tailor do not have any physical contact [*interview*].

Since customer needs are better met and product returns due to misfits might be avoided, there is also potential for reducing waste. By minimizing waste and reducing the carbon footprint associated with shipping and returns, virtual dressing rooms can possibly contribute to a more sustainable fashion industry. However, this improved convenience and access to fashion items for customers might also further foster (over)consumption practices and to date consumer behaviour analyses are mainly employed to boost sales, so caution is advised when assessing of the sustainability implications of these technologies (KPMG, 2021).

When it comes to actual uptake of digital fitting rooms and VR by industry, however, some of the interviewees active in retail state that both technologies are still in its infancy and need to be further developed to match their operating context *[interviews]*.

Several technologies improve information disclosure to customers. Barcodes, QR codes or IoT enabled RFID tags and NFC chips can be attached or embedded in textile products. By scanning the code or tapping a smartphone against the tag, a webpage will open to provide the customer with product information on origin, material composition, production chain, life cycle assessment or repair guidelines (KPMG, 2021). As indicated by one of the interviewees, most brands have a lot of data in their Enterprise Resource Planning (ERP) systems, but they are often not aware and it is often not structured or aggregated. It should be determined which information they are willing to share with the customer, and which information is relevant for the customer *[interview].* Adding AR or VR technology to the mix, connecting to the  identity tag on a garment can organize the whole supply chain of the garment in a virtual or augmented reality experience (PricewaterhouseCoopers, 2020). Codes and tags are also instrumental in enabling Digital Product Passports, as introduced by the ESPR.

Tags can also be used to facilitate product and customer tracking. While to date brands have little trace of who enters their (physical) shop, what they look at, for how long, what they try on and put back, digital technologies allow for better tracing the behaviour of visitors and potential customers. By using IoT-enabled tags, consumer behaviour can be tracked and analysed, informing the retail process (e.g. which sizes or colours sell better in which regions) and again providing information on emerging trends and consumer demand, which can then be fed into the design and production process (Gür, 2023). Alternatively, tags can be read by service robots, guiding customers to the desired products by voice command or to summon a “real” employee for personalized help (KPMG, 2021).

RFID technology will also impact internal company processes, such as checking product availability and monitoring stocks. The tag can contain product number and other data, can be read contactless by a reader. This will simplify complex inventories due to many sizes, colours and models, and make internal processes more efficient and stock inventories more accurate. It can also fight counterfeit as products can be scanned to proof their authenticity (KPMG, 2021). Combining RFID with AI and IoT can create predictions on customer demand based on previous and real-time data (Casciani et al., 2022). It also allows for real-time inventory tracking, meaning that retail, warehousing and logistics processes can be managed more easily and accurately.

Artificial intelligence (AI) and machine learning algorithms analyse consumer behaviour to offer personalized recommendations, improving customer satisfaction and boosting sales (Akhtar et al., 2022). AI will also play a key role in the setup of dynamic pricing (KPMG, 2021). Additionally, advanced AI is able to automatically predict what type of products will be in high demand and require reordering, based on consumer data from stores. Nowadays, current production and deficient forecasting methods are part of the cause of large amounts of unsold, and subsequently destructed, textiles. Better demand forecasting, powered by AI and big data analytics, allows companies to predict trends and consumer preferences accurately, avoiding misfits between production and demand that lead to unsold stocks (ETC/CE, 2024b). Finally, A leading use case for generative AI, as identified by fashion executives, is enhancing shopping experiences through AI-powered product discovery and customer search (McKinsey & Company and BOF Insights, 2024).

It is estimated that about 4-9% of produced garments are never sold (ETC/CE, 2024b; EEA, 2024). Minimum order quantities and long lead times makes it challenging for brands to order the right amounts, and there is a general lack of knowledge on consumer behaviour and preferences. Brands typically only know what sells after the first week of launch, and at this point it is too late to reorder within the season, which leads brands to rather order too much than too little. Moreover, factories require a lot of time to set up for production, which reduces their adaptability and ability to produce small batches on demand [*interview*]. As a result, there is often a mismatch between what has been produced by the industry and what consumers actually want, creating volumes of unsold garments nobody wants to [*interview*].

Feeding in trend predictions in AI systems can improve demand-forecasting, allowing a better match of new designs and production volumes with actual customer demand. Some ultra-fast fashion brands capture vast volumes of consumer data from social media, which get directly integrated into their design and decision-making process, allowing them to be on top of emerging trends [*interview*]. This example immediately unveils a potential drawback of the combination of AI-forecasting with fast design and production cycles: it has the potential to fuel ultra-fast fashion and encourage even faster changing trends and more overconsumption.

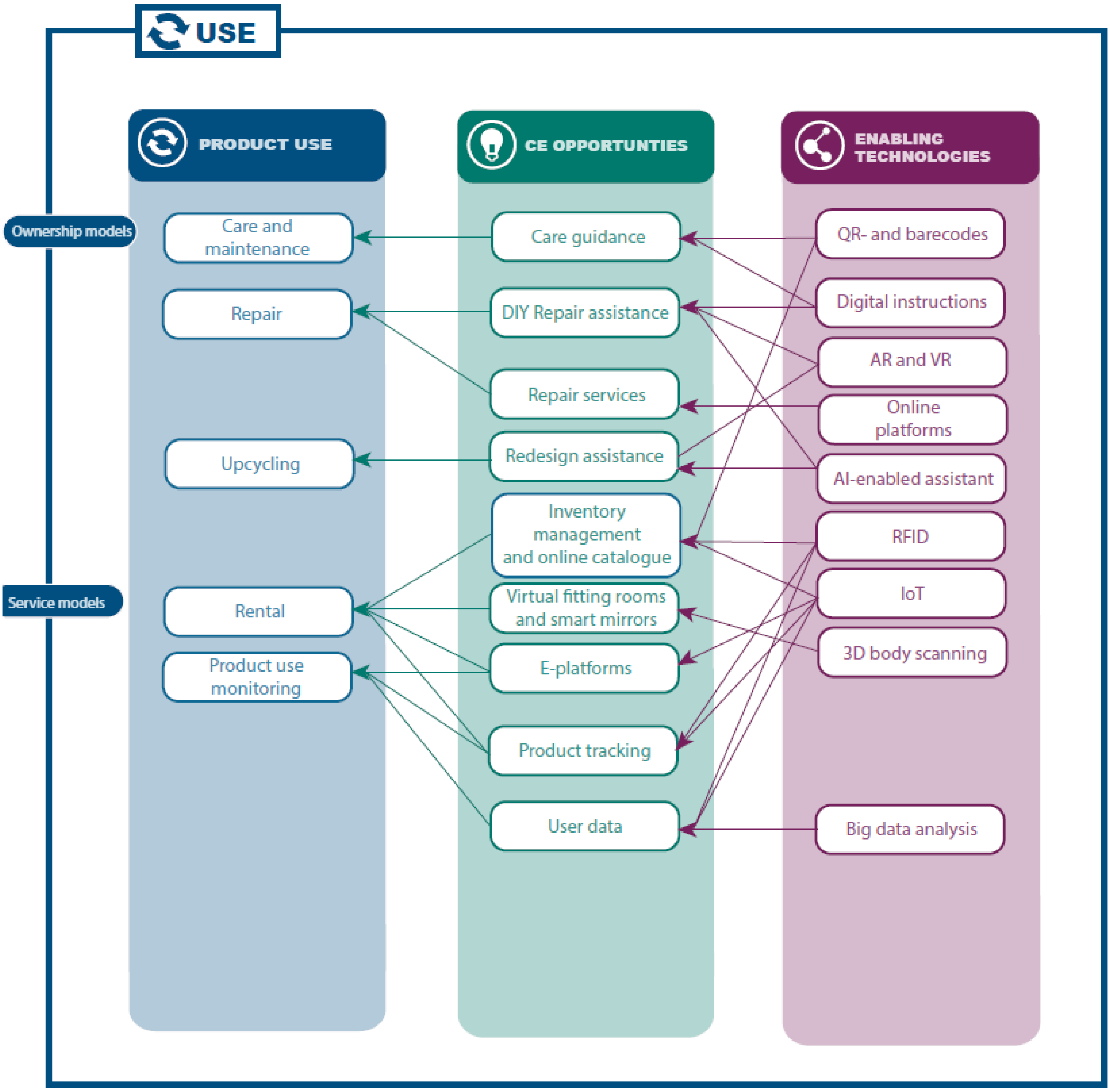
### Product use

Digital technologies can also play a role during the use phase of a textile product (Figure 3.5), for example in improving maintenance and care, supporting repair or facilitating textiles services. RFID and wearable sensors, connected through IoT, as well as AI and AR enable the collection of user data, monitoring product performance, as well as -in some cases) wearer’s health, and tracking of user behaviour, product diagnosis, digital care and repair guidance for users, and efficient product lifecycle management (Ghoreishi and Happonen, 2022; Fernández-Caramés and Fraga-Lamas, 2018). Enhanced care and maintenance are facilitated by IoT-enabled washing machines and smart care labels that provide users with precise washing and care instructions through AR/VR applications, ensuring optimal garment upkeep. All these aspects contribute to optimised product performance and use.

Digital platforms play a pivotal role in facilitating textile rental and repair services by streamlining operations and enhancing customer experience in service-based models (Arrigo, 2021). This brings opportunities for brands to become a partner and service-provider to their customers, offering styling advice, tailoring, maintenance, repairs, replacements but also resale and recycling (Charnley et al., 2022). Many of these services have traditionally been the responsibility of the consumer, however, in the market for professional and technical textiles, such as workwear or hospital linen, textile products are often supplied in a service-model. Depending on the product category, rental models may be suitable (e.g. occasional or seasonal clothing, skiing wear, etc.). Developing such services requires a good knowledge of customer needs and preferences, convenient services and good communication.

Rental platforms enable easy access to a wide range of garments through online catalogues, allowing customers to browse and select items conveniently from their devices. Advanced inventory management systems powered by artificial intelligence (AI) ensure efficient tracking and availability of rental items, reducing the likelihood of stockouts and improving service reliability (Arrigo, 2021; PricewaterhouseCoopers, 2020). Moreover, performant digital platforms incorporate user-friendly interfaces that simplify reservation, payment, product tracking and return processes, increasing use efficiency across multiple users (Rantala et al., 2023). Real-time communication via mobile apps or websites keeps customers informed about rental status, delivery schedules, and return options, enhancing transparency and trust (PricewaterhouseCoopers, 2020). By leveraging these digital tools, textile rental services not only offer convenience and flexibility but they can also contribute to sustainability by promoting longer use of clothing. On the other hand, rental systems can have higher impacts due to more intensive maintenance practices, such as dry cleaning (Amasawa et al., 2023).

Figure 3.5 Use of digital technologies in the use stage of textiles



**Source:** VITO/CSCP/ETC-CE

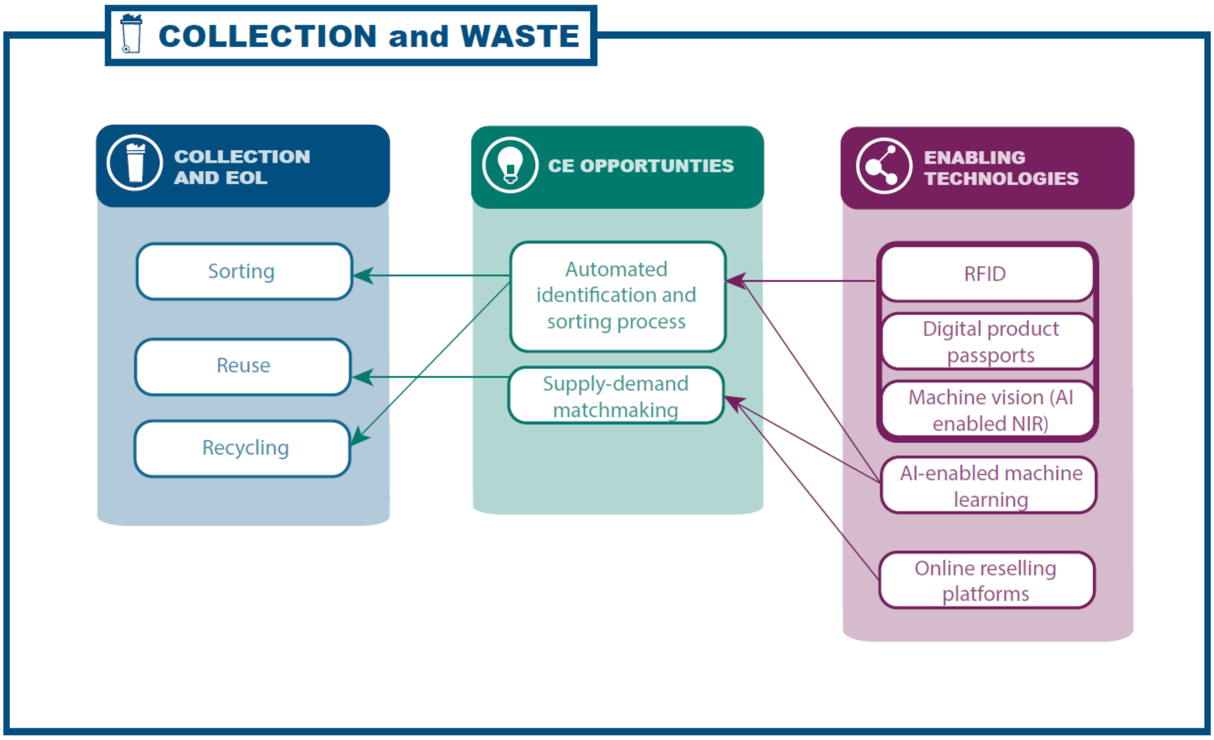
Repair platforms enable easy scheduling of repair services through online portals or mobile apps, allowing customers to submit repair requests and track the progress of their items in real time. AI-powered algorithms can assess garment damage remotely, providing accurate cost estimates and repair recommendations based on digital images or descriptions submitted by users. Moreover, digital platforms connect consumers with skilled repair professionals or workshops, as well as assist in streamlining logistics with auto-generated shipment labels, for example. This aspect is crucial, as “Smooth reverse logistics is key to nudge people to repair more”. For online repair companies working B2B, a large part of their value proposition is the possibility to integrate the digital ordering system seamlessly with the brands website [*interviews*]. Also for DIY repairs, detailed tutorials and guides on garment repair techniques could be provided online, empowering consumers to undertake minor repairs themselves, thereby extending the lifespan of their clothing. A combination of AI-enabled fault diagnosis with AR technology to guide repair activities is also a possibility (Bresanelli, 2018), while AR technology could also be combined with AI-design guidance for the redesign (or 'upcycling' of garments beyond repair (Gür, 2023). 3D printing technologies may be used for repairing as well as for manufacturing spare parts, such as buttons or zippers.

### Collection, sorting and waste processing

The EU 2025 obligation for the separate collection of waste textiles will impose challenges to the organization and capacity of collection systems, sorting and recycling installations. Moreover, the bulk of collected item is expected to be of mixed quality. Current practices in textiles waste management are mostly low-tech. Sorting is often still a manual process, in which an operator decides for each individual item if it is suitable for resale or bound for recycling. Textile collectors and sorters are also disconnected from textile designers and manufacturers. Sorters are obliged to work reactively to what they get as input, adjusting their sorting processes to the best of their ability, while products are typically not designed or made for easy sorting or disassembly, which complicates the process.

While sorting for reuse is still a very manual process, several digital technologies can enhance the take-back, sorting and end-of life processes of textiles, especially for preparation for recycling (Wojnowska-Baryła et al., 2024). These include automated sorting processes using digital identification technologies, such as labels or tags (e.g. RFID), and machine vision using near infrared (NIR) and hyperspectral imaging (Bonifazi et al., 2022). Digital product passport will be established following the ESPR and it will play an important role in streamlining textile end of life as well (Figure 3.6).

**Figure 3.6 Use of digital technologies in the collection, sorting and waste processing of textiles**



**Source:** VITO/CSCP/ETC-CE

Currently, textile sorting is mostly manual, capital-intensive, and time-consuming. Digital identifiers, such as RFID tags or QR codes, on textiles can significantly reduce processing time to identify composition of products, increasing capacity, and lowering costs (Xu et al., 2022). This system also enables detailed tracking of a product's lifecycle, fostering new circular business models. By delivering both scale and high-quality feedstock, digital identification technologies are essential for automating and tracking sorting and recycling, meeting the growing demand efficiently (Avery Dennison and TEXAID, 2024).

Machine vision and near-infrared (NIR) spectroscopy are at the forefront of automated sorting technologies, enabling the rapid and precise identification of textile types based on fibre composition and colour (Niinimäki et al., 2023; Rantala et al., 2023) *[interview]*. This precision sorting is crucial for ensuring that high-quality recycled materials are produced, as mixed or contaminated textiles can significantly impact the yield of recycling processes and the recycled output. Image recognition technologies further aid in sorting by identifying specific garment features or brands, ensuring that items are directed to the appropriate recycling or remanufacturing processes. Moreover, if take-back systems could be organised in such a way that items could be digitally labelled even before they arrive at the collection point, brands would be able to initiate new systems, such as collection for resell or repair [*interview*].

Most of the value will be created through reuse and resale. Digital solutions can help to find the right reuse(r) or for the right product. Reuse is not only about evaluating something to be reusable or not, the main issue is to find the perfect user, making it primarily a matchmaking problem. Digital peer to peer reuse platforms enable such matchmaking between consumers, enhancing reuse. However, from the angle of the waste management business there is a downside, because such platforms enable the consumer to skim off the best products on which they made most of their margin in the past, forcing them to also reconsider their business model *[interview]*.

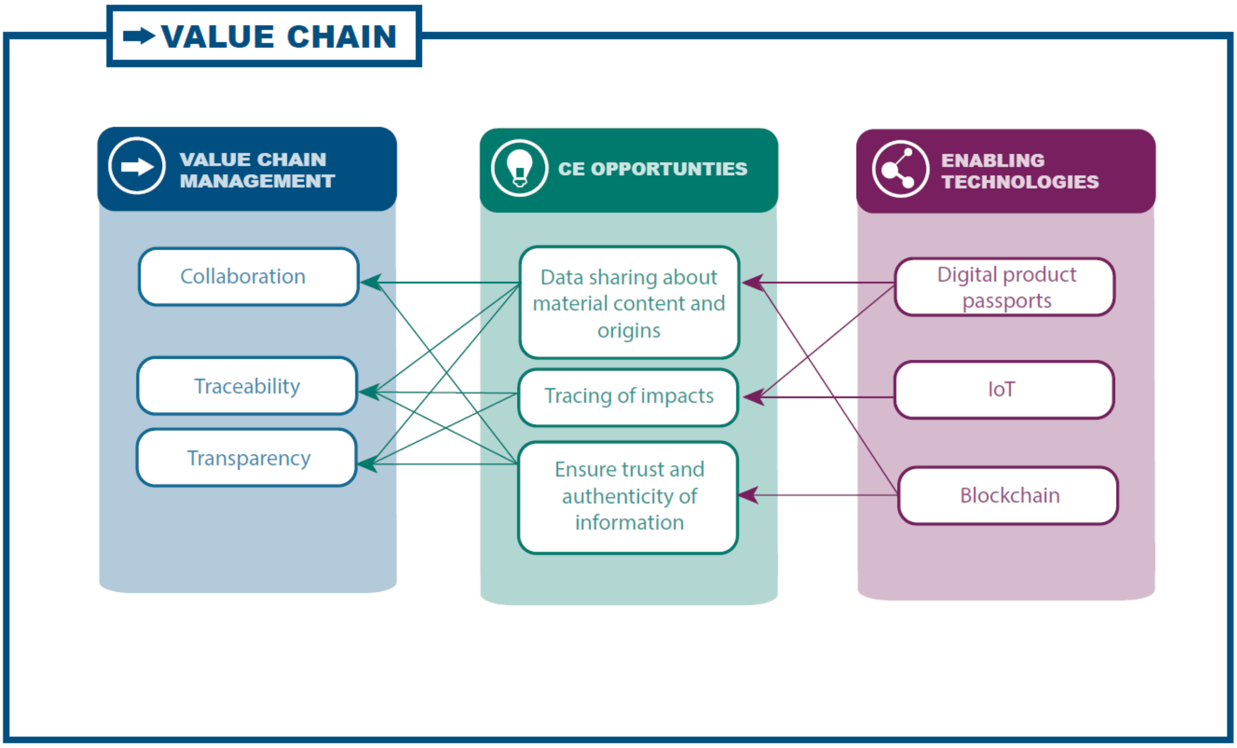
Finally, marketplaces for recycled materials are key in creating a mature market for secondary resources, connecting suppliers of high-quality recycled fibres with manufacturers looking to incorporate sustainable materials into their products.

### Cross-cutting: Value chain management, collaboration and transparency

Digital technology can enhance value chain transparency, addressing the complexities of the global fashion industry (Figure 3.7). Many fashion brands have a very limited visibility on their supply chain. However, upcoming regulatory requirements, including the Corporate Social Responsibility Directive (CSRD), Due Diligence Rules, information requirements and digital product passports in the context of the Ecodesign for Sustainable Products Regulation (ESPR), the EU Deforestation regulation, the EU Forced Labour Regulation, and verification and substantiation of voluntary green claims, will drive companies to adopt automated, digital technologies to collect, manage and share product information with their customers and collaborators to guarantee traceability, transparency and certification. These advancements will enable tracking and tracing of emissions, environmental and social impacts, and resource utilization, supporting value chain actors in making informed decisions, optimizing processes, collaboration and identifying opportunities for circularity, as well as increasing consumer acceptance (Antikainen et al., 2018).

Technologies like blockchain, IoT, cloud computing, and AI collaboratively manage detailed product information, ensure data authenticity, verify identities, enable secure multi-party transactions, and measure sustainability. For example, IoT sensors can track a fashion product from sourcing to production, distribution, and finally to the shop. Each transaction in this flow is recorded on an unchangeable blockchain, creating an immutable supply chain that ensures product authenticity and integrity. This system also supports the use of DPP and, when e.g. combined with RFID, can increase process efficiency and trustworthiness (Saccani et al., 2023). This makes the technology instrumental in combating counterfeiting, a significant issue in the industry (PricewaterhouseCoopers, 2020).

Figure 3.7 Use of digital technologies in value chain management and transparency



**Source:** VITO/CSCP/ETC-CE

Intelligent digital labels empower brand owners and retailers to streamline supply chains, enhance transparency, and support omnichannel sales models. They improve product authenticity, create innovative retail experiences like self-checkout, and engage consumers post-purchase. Additionally, these labels are crucial for improving traceability in collection, takeback services, and sorting processes for reuse or recycling. Most used identifiers are universal product codes, Radio Frequency Identifiers (RFID), and 2D barcodes. Identifiers could provide information about the fabric and materials and how the products are manufactured. The information about recyclability and recycling options could be added to the identifiers. (Jia et al. 2020.) RFID tags can also help in product availability tracking and in analysis of customer behaviour (Landmark and Sjøbakk, 2017). Product information can be stored by creating a digital twin of the product, based on which RFID robots can create an inventory, track and localise products, allowing users to virtually navigate the shop (Pous et al., 2023).

Business experts estimate that in five years more than 50 % of fashion products will be RFID-tagged thanks to improved cost efficiency. The prediction that clothing with NFC chips will become "smart" points to a world in which the Internet of Things is becoming commonplace. According to this idea, garments, merchandise carriers, employees' terminals and customers are able to communicate with each other. For example, shelves can independently contact the scheduling system when stock levels fall below minimum levels. Garments in the shop tell the service staff if they are placed on the wrong display table. The sales department is informed about which items are often tried on but ultimately not bought (KPMG, 2021). A point of attention is  that these tags have limitations in washing resistance, so they may no longer be readable at end-of-life depending on their quality (Björninen et al., 2014).

Nonetheless, interviewees indicate that there are some challenges and considerations to take into account when introducing identification technologies: which carriers to use, how to integrate them and make sure they are not removed? It is recommended to use different tags for consumers than for industry players like sorters and recyclers *[interview]*. A physical data carrier/tag like RFID or NFC that allows for traceability of a product is relatively costly in comparison to the production cost of a garment.

*[interviews]* A customer-facing QR code, on the other hand, is less costly and therefore actively considered today. They allow for storytelling and nudging towards consumers *[interview].*

Also here, the (environmental) externalities of the digital innovation itself (e.g. RFID tags, sensors and energy-consuming data management tools) should carefully be considered (Gür, 2023).

The Digital Product Passport (DPP), defined by the EU's Ecodesign for Sustainable Products Regulation (ESPR), is a digital record containing detailed product information, accessible through a unique identifier, for example using QR codes, NFC or RFID technology (European Commission, 2024a). It allows stakeholders—from raw material producers to end consumers—to access information electronically, aiding decisions on sustainability, circularity, and value retention, governed by specific data ownership and access rights. Depending on the product information requirements introduced under ESPR, the DPP may tell exactly what the item is, how old it is, what the composition is, etc. Currently, this information often is not visible anymore because the labels have been cut or washed out and are no longer readable *[interview],* an issue that also needs to be considered in the case of the DPP data carrier. The DPP promotes sustainable production, supports service and repair models, aids compliance verification, and enhances supply chain collaboration. These passports will enhance transparency and trust, providing reliable data that empower consumers to make informed decisions about buying, maintaining, repairing, and eventually recycling or repurposing their garments (Niinimäki et al., 2023; Vellanki and Gopinath, 2023). They will also have a key role in engaging and sharing information with recyclers and sorters, hence stimulating the creation and full implementation of the business model for recyclability and a secondary raw materials market. By streamlining reporting and enhancing data transparency, it facilitates circularity, helps calculate the impact of sustainable designs, and boosts the visibility of sustainable products (WBCSD, 2023; EURATEX, 2023). According to the ESPR, the DPP is crucial for achieving transparency and sustainability in the textile sector and the delegated act governing their introduction is still under preparation. It provides data to evaluate environmental impacts, combat overproduction, and prevent garment destruction, while also extending product life by managing repair information. As a result, DPP could offer a whole toolbox to better connect with the customer, potentially improving emotional attachment, longer use and better the maintenance [*interview*]. For waste management, DPP improves sorting accuracy by providing detailed content information, directing textiles to suitable recycling paths, and increasing the value of recycled materials (Niinimäki et al., 2023; WBCSD, 2023).

Nonetheless, introducing DPP to textiles remains challenging, especially if it aims to follow materials beyond garment use, given the recycling process breaks down fibers. Emerging technologies, like adding inorganic particles to fibers for unique spectral signatures detectable with NIR/VIS technology, could provide material integrity and traceability. This could enable brands to recover their materials in recycling and use digital twin technology for verification, potentially integrating AI for advanced analysis in the future (WBCSD, 2023).

Many interviewees recognize the need for DPP but several challenges still need to be overcome. One of the interviewed retailers indicated that the introduction of a DPP is conceived as both an opportunity and a challenge by industry. It is believed to be a great step towards transparency, but the need for documentation results in a high administrative burden, especially since the textile value chain is very complex with numerous upstream suppliers. There will be no time savings in the short term, but in the long term the collected data should provide greater efficiency *[interview].*

### Environmental and climate impacts of digital technologies

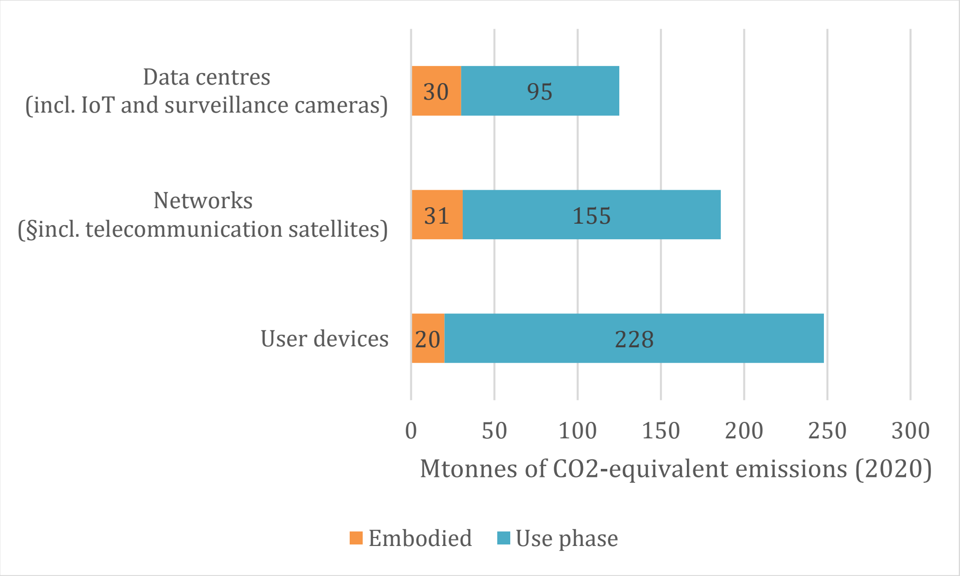
As touched upon repeatedly in previous sections, one of the drawbacks of the implementation of digital technologies for sustainability purposes, are the environment and climate impacts generated by (the use of) these technologies themselves. This next to the potential perverse effects they induce - like increased production and consumption - offsetting potential benefits of digitalisation in the textiles sector. The expansion of digital devices, data transmission networks, and data centres, along with the rise of computationally intensive applications like AI, contribute significantly to the growing environmental footprint of the ICT sector.

The environment and climate impacts of digital devices and technologies span their entire life cycle, from production (including raw material extraction, processing, and manufacturing) to usage and end-of-life disposal. The 'environmental footprint' of digital technologies reflects their direct impacts, such as energy and water consumption, use of raw materials – many of which are considered 'critical' for the EU (Carrara et al., 2023) -  greenhouse gas (GHG) emissions, and pollution from waste. Additionally, digital technologies also have indirect environment and climate effects across the different sectors in which they are applied, which can be both beneficial and harmful.

Estimating the precise environment and climate impact of the ICT sector is challenging due to lack of publicly available data and differences in methodologies and assumptions. For instance, estimates of the ICT sector's GHG emissions in 2020 range widely from 0.69 to 1.6 gigatons of CO2 equivalent, accounting for approximately 1.5-3.2 % of global emissions. The sector's impact on water use, a critical yet often overlooked aspect, is significant, affecting local biodiversity and livelihoods, especially considering the water-intensive nature of mining for digital device production (United Nations Conference on Trade and Development (UNCTAD), 2024).

As digital services expand globally, the consumption of energy and water for devices and ICT infrastructure has increased. For example, data centres and transmission networks, which operate continuously, account for a significant portion of the ICT sector's energy use and GHG emissions (Malmodin et al., 2024) (Figure 3.8). Emerging technologies such as blockchain, AI, 5G networks, and the Internet of Things (IoT) are expected to further increase data processing and storage demands, thereby amplifying the environmental footprint of the ICT sector. In particular, AI and machine learning require extensive computing resources, and their widespread adoption will necessitate a closer examination of their energy and water usage. For blockchain technology it should be mentioned that a major upgrade of the system called 'The Merge' in September of 2022 showed an instant reduction of the technology's energy consumption of 99%, significantly increasing its energy efficiency. This is mainly because so-called 'validators' no longer need energy-intensive mining equipment (EU Blockchain Observatory and Forum, 2023). It is nonetheless not clear how the system's energy consumption evolved in the months and years after this upgrade.

**Figure 3.8 Global Greenhouse gas emissions from ICT**



**Source**: Malmodin et al., 2024

Data centres are particularly energy-intensive, with the electricity consumption of the 13 largest operators (including Amazon, Alphabet, Microsoft, and Meta) more than doubling between 2018 and 2022 (United Nations Conference on Trade and Development (UNCTAD), 2024). The International Energy Agency (IEA) estimates that global data centre electricity consumption could more than double from 460 terawatt-hours (TWh) in 2022 to 1,000 TWh by 2026, partly due to the increased use of AI (IEA, 2024).

For water use impacts less information is available. Annual water consumption for data usage in  Europe is estimated to increase from 145.2 million cubic meters in 2020 to 546.7 million cubic meters by 2030 (Farfan and Lohrmann, 2023), another source states that the global AI demand may be accountable for 4.2–6.6 billion cubic meters of water withdrawal by 2027 (Li et al., 2023). Nonetheless, water use impacts are very context and location specific. In cooler regions like Northern Europe, free air cooling can be used for most of the year, significantly lowering water usage. In contrast, in warmer regions such as Africa and Southeast Asia, minimizing water consumption for cooling presents a greater challenge. In recent years, advancements in cooling technologies, combined with the increased temperature tolerance of certain IT equipment, have reduced dependence on water-based cooling systems. Alongside these innovations, alternative water sources like reclaimed wastewater and seawater are being investigated to address the significant water requirements of data centres (United Nations Conference on Trade and Development (UNCTAD), 2024).

Despite the perception of the digital economy as intangible or "virtual," it relies heavily on physical materials like plastics, metals, and minerals. The production of a single 2 kg computer, for example, can require up to 800 kilograms of raw materials (Justice et Paix, 2019). Key materials used for digital technologies, such as aluminium, cobalt, copper, gold, lithium, and rare earth elements, are considered critical for the transition to a low-carbon economy and will play a major role in the energy transition.

The demand for these materials is expected to surge, potentially exceeding the Earth's available resources. The World Bank projects that the production of minerals like graphite, lithium, and cobalt could increase by up to 500 % by 2050 (Hund et al., 2023), and the IEA anticipates a 120-fold increase in the consumption of platinum group metals (IEA, 2023). Further development of recycling technology and capacity for metals will be crucial to assure future production of batteries, permanent magnets, solar panels and electricity networks. It is estimated that Europe’s clean energy ambitions will require huge yearly amounts of metals by 2050, including a 350-fold increase for lithium and a 3-fold increase for cobalt (KU Leuven, 2022).
In summary, the ICT sector's environment and climate impact is substantial and multi-faceted, involving significant energy consumption, GHG emissions, water use, and raw material extraction throughout the life cycle of digital technologies. The sector's impact is expected to grow with the increasing adoption of advanced digital technologies, necessitating more sustainable practices and greater transparency in reporting environmental data.

The interviewees involved in this study confirm that the downsides of digitization in relation to circular economy and sustainability need to be considered. They highlight that the environmental and climate impact of digital activities is significant, and there is a risk of greenwashing. For example, virtual fashion and AR garments are often presented as resource efficient due to their full dematerialisation, however, environmental benefits remain far from proven [*interview*].

## 3.3 Digital technologies in support of circular business models

In literature, digital technologies are often acknowledged to be a helpful factor toward implementing sustainable and circular business models, whether by being a key enabler in creating new business models or merely contributing to the success or performance of existing ones (Broccardo et al., 2023). Especially in the view of further increasing e-commerce, a greater emphasis on circular business models is considered key to ensure environmental sustainability (United Nations Conference on Trade and

Development (UNCTAD), 2024). This chapter explores what role digital technologies play in business-model innovation within these circular textiles business models (Figure 3.9). To structure the discussion, four circular business model types for textiles are used (Box 3).

Many changes in value proposition (product/service, customer segments and relationships), creation & delivery (key activities, resources, channels, partners), and capture (cost structure & revenue streams) are triggered by the adoption of digital technologies. For example, value propositions shift to service-oriented, user-centric and network-based approaches, allowing for enhanced customer creativity, co-creation and interactive communication through platforms. Products or services can take a different, digital form, extending the traditional way of value delivery into the digital realm through digital platform-based services (e.g. virtual showrooms, online shopping, digital fitting services) or by creating new digital product offerings, such as AR-skins to wear only on social media (Casciani et al., 2022). Changes in value capture entail increased resource efficiency, increased productivity and optimization of operations, resulting in a shortening of lead times and costs savings due to automation and improved decision making in design and manufacturing. Additionally, new revenue streams can be developed based on new digital services or virtual clothes, or through software tools enabling dynamic pricing, subscriptions and performance-based contracting (Casciani et al., 2022).

### Box 3 Circular business models for textiles

**Longevity and durability:** These business-models aim at extending the lifetime of garments, through longer use, enabled through maintenance, repairability, or the enhancement of emotional attachment trough personalisation. Overall aim is to reduce consumption.

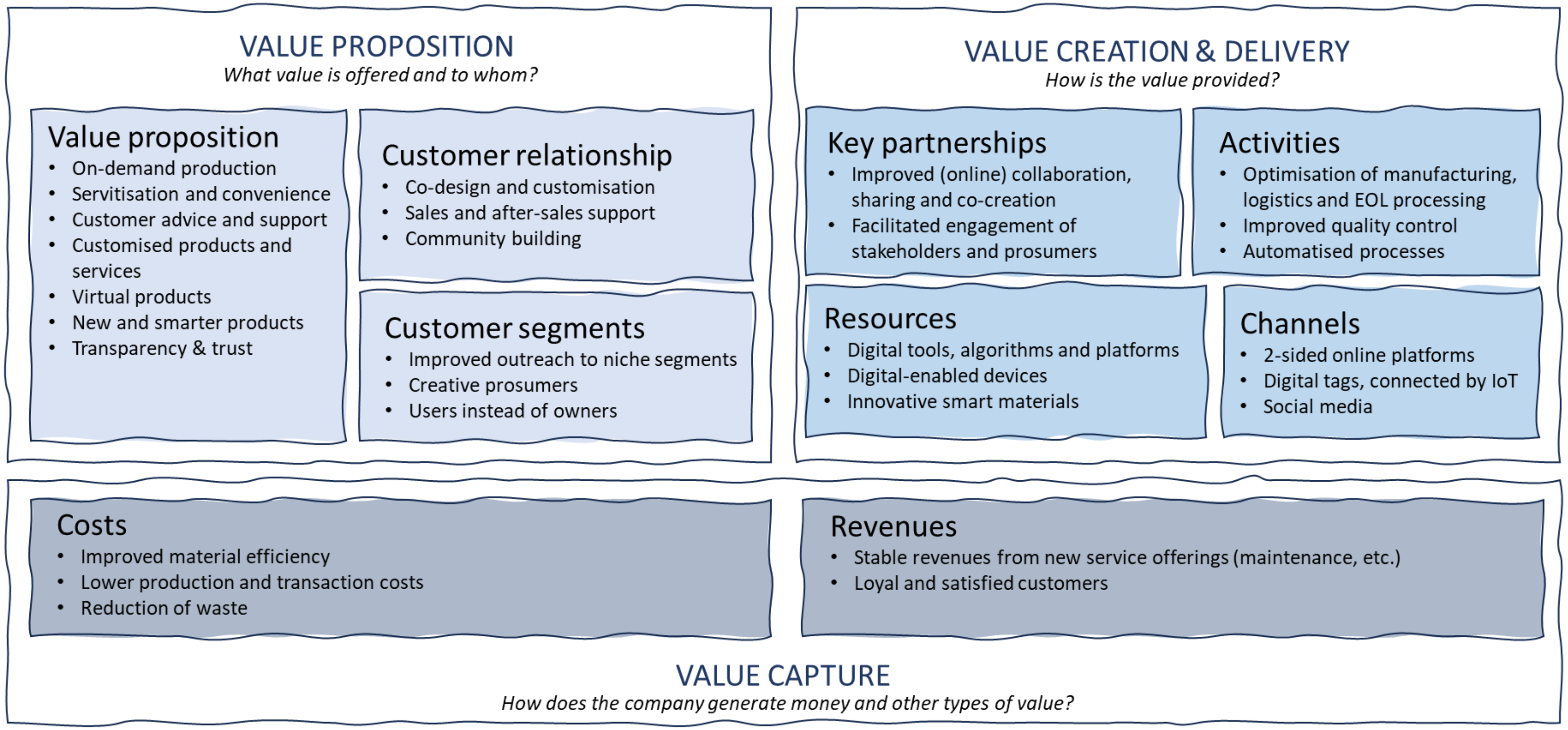
**Access-based models:** These business models are based on renting, leasing, and sharing of garments. Access-based models aim to lower consumption by increasing the use rate of existing product stock.

**Collection and resale:** Thes business models focus on extending the useful life of textiles beyond the first user, by organising collection systems aimed at reuse, such as second-hand retail.

**Recycling and remanufacturing:** When reuse is not possible, these models emphasize turning textile waste into parts for remanufacturing or recycled materials for re-spinning into new yarns and textiles.

**Source**: based on ETC/WMGE, (2021); EEA (2021); Coscieme et al. (2022)

**Figure 3.9 Effect of digital technologies on the different aspects of the Business Model Canvas**



VALUE PROPOSITION

*What value is offered and to whom?*

**Value proposition**
- On-demand production
- Servitisation and convenience
- Customer advice and support
- Customised products and services
- Virtual products
- New and smarter products
- Transparency & trust

**Customer relationship**
- Co-design and customisation
- Sales and after-sales support
- Community building

**Customer segments**
- Improved outreach to niche segments
- Creative prosumers
- Users instead of owners

VALUE CREATION & DELIVERY

*How is the value provided?*

**Key partnerships**
- Improved (online) collaboration, sharing and co-creation
- Facilitated engagement of stakeholders and prosumers

**Activities**
- Optimisation of manufacturing, logistics and EOL processing
- Improved quality control
- Automatised processes

**Resources**
- Digital tools, algorithms and platforms
- Digital-enabled devices
- Innovative smart materials

**Channels**
- 2-sided online platforms
- Digital tags, connected by IoT
- Social media

**Costs**
- Improved material efficiency
- Lower production and transaction costs
- Reduction of waste

**Revenues**
- Stable revenues from new service offerings (maintenance, etc.)
- Loyal and satisfied customers

VALUE CAPTURE

*How does the company generate money and other types of value?*

**Source**: adapted from (Broccardo et al., 2023; Davies and Doherty, 2019; Bocken et al., 2014; Osterwalder and Pigneur, 2010)

### Longevity and durability

This business model centers around the creation of textile products delivering a long product life, due to their durability, easy maintenance or repairability. A traditional product sales model, through physical or online shops, is often combined with the offering of maintenance and repair guidance or services to customers. Product customisation can also be a feature to ensure consumer-attachment. Enabling longer product lives decreases the rate at which products are discarded, reducing the amount of waste generated, and potentially also reducing consumption and buying new items (ETC/WMGE, 2021). Also potential second hand value can be an attractive feature. However, it is important to point out that durability of products alone does not necessarily mean that consumers purchase less products, or that they only replace products when they are no longer fit for use.

Within the 'Longevity and durability' business model, digital technologies are mainly deployed to help extending the life of products (Table 1). Digital design tools, such as CAD, 3D modelling and AI can assist designers in making conscious material and product design choices that increase products' wear and tear resistance, timelessness, ease of maintenance and repairability, ensuring longer-lasting garments. Open-source fashion and user-centric design processes combined with made-to-order manufacturing can facilitate a direct relationship between brands and buyers, allowing for personalized, customized, and exclusive designs, empowering consumers to actively participate in the fashion creation process and potentially creating a stronger product attachment , increasing the likelihood that users want to keep products for longer (Casciani et al., 2022). Still, it is important to note that higher product attachment does not necessarily lead to reduced consumption or production. Virtual fitting and customization services assure a good fit, even in the case of online sales, reducing the risk of returns. During product use, complementary services, such as digital care and repair guides, AI-enabled repair assistants and platforms offering maintenance and repair services support users in extending product lives.

Table 1 Impact of digital technologies on the business model 'Longevity and durability'

| Product or service offering | Digital technology | Environmental impact* |
|---|---|---|
| **Durable, repairable and long-lasting designs** | CAD - AI | Longer product life, potentially reduced consumption |
| **High-quality products** | Robotics in production, AI-enabled quality control | Reduction of production waste and better monitoring/avoidance of defects |
| **Accessible product information** | IoT enabled RFID tags | Enable conscious consumer choices |
| **Virtual fitting rooms, magic mirrors** | AI, AR-VR-enabled assistants | Reduction of returns |
| **Maintenance and care instructions** | Digital care guide, AI/AR-enabled assistant | Longer product life |
| **On-demand spare parts** | 3D printing | Longer product life, waste reduction |
| **AI-assisted repair guidance** | AI/AR-enabled assistant | Longer product life, customer engagement |
| **Accessible repair services** | platform | Longer product life, customer support |
| **Customised products, creating customer attachment** | CAD, 3D printing/knitting/weaving, distributed manufacturing through IoT, 3D body scanning | Potential avoidance of overproduction, avoiding returns, longer product life through attachment, customer engagement and co-creation |

*Note: the environmental impacts associated with the digital technologies themselves (i.e. energy and water use, raw materials) are not mentioned in this table, but remain trade-offs that needs to be taken into account when evaluating overall impact.

### Service/access-based models

Service and access-based models provide a value proposition focused on user experience and product performance without the cost of ownership, making products more accessible and affordable. Examples include renting of workwear, hospital or restaurant linen, single-occasion clothing, and baby clothes or reusable diapers. They can also entail garment leasing or wardrobe sharing. Revenues in these models are generated through periodic rental or leasing fees and additional services like maintenance or repair, offering convenience and hassle-free performance, which is particularly beneficial in business-to-business settings. By increasing the use frequency of products through shared use and reuse, service models can lead to reduced consumption overall. These models also have the potential to decouple profit generation from production and sales volumes, which shifts company incentives towards high-quality, durable products which are easy to maintain and repair, extending product lifespans, as well as the implementation of take-back systems (ETC/WMGE, 2021; EEA, 2021).

On the other hand, while rental and service models have the potential to intensify garment use without the need for each user to buy new items, reduced consumption is not guaranteed. For example, platforms offering a subscription formula might nourish consumers' urge for new, in-fashion items, indirectly stimulating consumption. Also, most customers of renting platforms are attracted to the ability to regularly change their wardrobe, not by sustainability reasons [*interview*]. Moreover, intensified transactions and maintenance in the context of service models could increase impacts (transport, increased washing at high temperatures, etc.).

Product-service systems (PSS) have been acknowledged as an important business model innovation that could greatly benefit from digital technology adoption (Gür, 2023; Chauhan et al., 2022; Antikainen et al., 2018; Bressanelli et al., 2018). The integration of Big Data, data mining, data analytics, the Internet of Things within access-based business models offers significant opportunities for advancing sustainable value creation, value capture, and the circular economy (Arrigo, 2021) (Table 2). In PSS systems, digital technologies enable service providers to collect data that can be used in product innovation, service optimisation and end-of-life management of product portfolios, as well as increasing customer satisfaction within the service offering (Antikainen et al., 2018). At the same time, these technologies support the scaling of such models (ETC/WMGE, 2021), for example, by facilitating sharing practices (Akhtar et al., 2022) and collaborative consumption through digital platforms (Arrigo, 2021). Thanks to digital solutions, collaborative consumption has transitioned from local, physical marketplaces to global online communities via digital platforms. These platforms are crucial for all aspects of product sharing, swapping, or lending activities, including browsing, ordering, payments, deliveries, and business management. Additionally, they serve as vital channels for marketing, attracting target customer segments, customer profiling, personalized communication, and customer service, such as preventive and predictive maintenance (Arrigo, 2021; Bressanelli et al., 2018). Smart, connected products allow producers to track, monitor, control, analyse and optimize product performance and collect usage data (Antikainen et al., 2018; Bressanelli et al., 2018). Full transparency, traceability and authenticity of product data is crucial to optimise service performance and reduce environmental impact during the use phase, as well as to manage liabilities and warranties. This transparency and trust could be provided by digital product passports, artificial intelligence and blockchain (Arrigo, 2021).

### Table 2 Impact of digital technologies on the business model 'Service/access-based models'

| Product or service offering | Digital technology | Environmental impact* |
|---|---|---|
| Renting or subscription services, pay-per-wear or per-period | Online platforms, RFID tags, inventory software, IoT, big data analytics | Reduced consumption, Affordability of special items, access to high-quality garments |
| P2P swapping platforms | Platforms, 2-side marketplaces | Reduced consumption |
| Maintenance services | IoT, platforms | Lifetime extension, Accessible and convenient maintenance services |
| AI and AR-supported virtual shop assistants | IoT based consumer behaviour analytics, big data analytics | Reduced returns |
| On-demand production | 3D printing/knitting/weaving, 3D body scanning | Reduced returns, prevention of unsold stock, inclusive sizes |
| Open-source fashion design | CAD, AI-assisted co-creation platforms, | Reduced returns, personal expression and attachment, prevention of unsold stock |
| Virtual fashion | VR, AR, NFTs | No material use, no waste |

*Note: the environmental impacts associated with the digital technologies themselves (i.e. energy and water use, raw materials) are not mentioned in this table, but remain trade-offs that needs to be taken into account when evaluating overall impact.

### Collection and resale

Business models related to resale focus on extending the useful life of textiles beyond the first user. Several types of take-back initiatives collect reusable garments for preparation for reuse, e.g. from selective or general bring-back schemes in shops to curb-side collection by municipalities or charity organisations. Various branding labels, such as pre-owned, pre-loved, vintage, and eco, are frequently applied to items to enhance their attractiveness. Online platforms and apps facilitate the resale, donation, and exchange of garments, promoting reuse and extending the life cycle of textiles. Peer-to-peer second-hand sales are also very common and have moved from tedious adverts in the local paper to convenient, international online marketplaces. The reuse of products reduce the need for new ones, reducing production impacts (ETC/WMGE, 2021).

Digital technologies can help to address critical challenges in collection and resale business models for textiles and clothes, such as high logistics and sorting costs against relatively low revenues (Table 3). For instance, advanced data analytics can optimize collection routes based on real-time demand and geographic data, reducing operational expenses. Automation technologies like AI-powered sorting machines can, autonomously or alongside human operators, streamline the process of checking, categorizing and pricing items, improving efficiency and reducing labour costs.

Digital, online re-commerce platforms enable matchmaking between supply and demand for reusable goods and facilitate secure transactions, increasing convenience, trustworthiness, and consumer acceptance as well as attracting broader target customer segments beyond their physical location (Bressanelli et al., 2018), thereby increasing sales potential and mitigating the impact of low margins. As a result, many established brands are launching their own re-commerce platforms for second-hand resales (Eunomia, 2022). These platforms leverage AI, cloud computing, and blockchain technology to connect brands and consumers who share sustainability values, fostering new business models centered on rental, reuse, and resale of fashion products (PricewaterhouseCoopers, 2020). Additionally, peer-to-peer platforms use digital technologies to facilitate direct consumer-to-consumer transactions, further boosting the accessibility and viability of textile resale. By leveraging user-generated content, such as reviews and ratings, these platforms build trust among buyers and sellers, fostering a vibrant community centered around sustainable consumption practices. Moreover, digital payment systems integrated into these platforms streamline transactions, enhancing convenience and encouraging more frequent exchanges. Overall, peer-to-peer platforms harness the power of digital technology to democratize access to the resale market, empowering individuals to participate actively in the circular economy of textiles and clothes. Some platforms, like Vinted, focus on peer-to-peer exchanges and reach approximately 45 million users across 12 European countries (Eunomia, 2022).

### Table 3 Impact of digital technologies on the business model 'Collection and resale'

| Product or service offering | Digital technology | Environmental impact* |
|---|---|---|
| B2C Convenient take-back/buy-back collection systems | DPP | Waste reduction, improved EOL management |
| B2B reverse logistics of used clothes to retailers or manufacturers | Digitalised take-back systems and receipts | Improved EOL management |
| Automated or operator-supporting sorting equipment | Automated, AI-enabled sorting technologies | Waste reduction, increased reuse and improved recycling |
| Re-commerce platforms, enabling the resale, rental, and return of second-hand fashion items | digital platforms, leveraging AI, cloud computing, and blockchain technology | Increased reuse, affordability |

*Note: the environmental impacts associated with the digital technologies themselves (i.e. energy and water use, raw materials) are not mentioned in this table, but remain trade-offs that needs to be taken into account when evaluating overall impact.

### Recycling and remanufacturing

These models emphasize turning textile products that cannot be reused for their original purpose into parts for remanufacturing or 'upcycling' or into recycled fibres for re-spinning and use in other products. Both reduce the demand for virgin raw materials and prevent textile waste generation (ETC/WMGE, 2021). Remanufacturing utilizes waste materials creatively, emphasizing sustainability and unique designs. They leverage eco- and designer-branding as value propositions to justify premium pricing while accessing low-cost or free raw materials through partnerships with waste suppliers. Often social economy actors are involved in the manufacturing. Recycled textiles incorporate recycled fibres into mainstream designs to reduce environmental impact. Though less visibly distinctive than upcycled items, they also attract eco-conscious consumers seeking products with a lower environmental footprint (ETC/WMGE, 2021).

Digital technologies can support both remanufacturing and recycling approaches (Table 4). Remanufacturing and upcycling initiatives face significant challenges and thus far have remained niche due to the need for customized, labour-intensive processes requiring specific skills, tools, and space. Challenges include uncertain material sourcing, quality control issues and labour-intensive tailored designs, leading to low profitability (Singh et al., 2019). Digital technologies can help to mitigate some of these challenges by improving efficiency and productivity, and by supporting market creation through matchmaking and connectivity between remanufacturers and their material suppliers as well as their customers. For instance, online platforms and digital marketplaces can connect upcyclers with reliable suppliers and provide real-time market insights. Tools like CAD software can streamline design customization and reduce production time, while digital fabrication technologies enable small-scale production without large facilities. AI and AR-assistance for manual labour can further enhance productivity. Education through online courses and virtual workshops can impart technical and business management skills, fostering entrepreneurship. Collaboration platforms and digital networks facilitate knowledge sharing and resource pooling among upcyclers, enhancing collective capabilities (Singh et al., 2019). Also, in recent years, there has been a growth of online platforms specializing in handicrafts, including remanufacturing and upcycling. These platforms provide accessible marketplaces for home artisans and small-scale entrepreneurs to showcase and sell their upcycled products globally (ETC/WMGE, 2021).

Despite technical barriers in textile recycling, advancements in digital identification, sorting technologies, and recycling processes hold promise for scaling up recycled fibre production and meeting market demands more efficiently. Advanced data analytics enable efficient route planning for collection trucks based on real-time data on demand and geographic patterns, optimizing logistics and reducing costs. AI-powered sorting technologies can accurately categorize textiles based on material composition and colour, ensuring homogenous outputs for recycling complying with process requirements. Digital platforms facilitate transparent and traceable supply chains, connecting textile waste suppliers with recycling facilities and manufacturers. In the context of recycling, it is especially important to know the chemical composition of products and chemicals that have been used during production processes. For instance, blockchain technology can track the entire lifecycle of recycled textiles, ensuring authenticity and compliance with sustainability standards. Online marketplaces for recycled fibres and fabrics enable easier procurement for textile manufacturers. Moreover, digital tools like 3D modelling and virtual simulations aid in designing and prototyping new products made from recycled materials.

**Table 4 Impact of digital technologies on the business model 'Recycling and reuse of materials'**

| Product or service offering | Digital technology | Environmental impact* |
|---|---|---|
| Automated sorting technology enabling fast and accurate textile sorting for recycling | Robotics, NIR machine vision, Machine learning and AI, automation | Improved recycling |
| Tracking products throughout the sorting and recycling process | RFID tags and DPP | Reduces time and resource loss, improved recycling |
| Optimisation of recycling processes | IoT, RFID tags | Reduces energy and water use, reduces waste |
| Digital tools for redesign and upcycling of existing garments | AR, AI | Material savings through remanufacturing, waste reduction |
| Upcycling and remanufacturing on demand | CAD, 3D printing | Waste reduction |
| Design-support tools assisting in better use of recycled fibres in designs and design-for-recycling | IA-added design, 3D knitting technologies capable of using recycled fibres | Virgin material savings |

*Note: the environmental impacts associated with the digital technologies themselves (i.e. energy and water use, raw materials) are not mentioned in this table, but remain trade-offs that needs to be taken into account when evaluating overall impact.

## 3.4 Implementation barriers

Despite growing industrial interest, at scale implementation of digital solutions pose specific challenges or difficulties hindering their adoption (Geissdoerfer et al., 2018; Broccardo et al., 2023). For example, a survey among 326 SMEs[16] showed that only about 14% of textile companies in the sample adopted IoT, mainly for inventory tracking, predictive maintenance or process monitoring. About 13% reported using robotics in product assembly (sewing), printing and product inspection. Only 8% used AI or AR/VR technologies, for example in product design, while less than 5% reported use of digital twins. On the other hand, online platforms for e-commerce were used by almost 40% and cloud software by slightly over 30% (Izsak and Moreno, 2024).

In the following paragraphs, these barriers are discussed, categorized based on an adapted classification system from Antikainen (2018) and building upon insights from the interviews conducted in the light of this research.

---

[16] This survey was part of the European monitor of Industrial Ecosystems (EMI) project, initiated by the European Commission, Directorate General for Internal Market, Industry, Entrepreneurship and SMEs and the European Innovation Council and SMEs Executive Agency (EISMEA) (Izsak and Moreno, 2024)

### Financial barriers

Cost-related aspects of digitization are a major issue for the fashion industry, which faces low profit margins, high speed, and intense competition *[interview*]. Industry 4.0 technologies are often inaccessible to many producers due to high investments and the specialized skills required (Hossain et al., 2024). While time-consuming setups and minimum order quantities (MOQs) exceeding demand are not seen as significant challenges [*interview*], the high costs of digital technologies limit their adoption. Larger brands, despite having the financial resources to invest in these technologies, often lack the motivation to do so, as they remain profitable through traditional methods [*interview*]. Integrating digital technologies across the supply chain is particularly expensive and time-consuming [*interviews*]. While investments in digital tools like printing machines are significant, the primary costs are often related to the transformation required to integrate these technologies and develop a skilled workforce [*interview*]. Additionally, the cost of technologies like RFID traceability labels remains too high in relation to production costs, despite their benefits in traceability and complementarity with QR codes [*interview*]. Large-scale adoption of DPP will be mandatory as part of the ESPR, requiring substantial investments and skilled personnel. Setting a cost-effective price for tags to ensure a positive return on investment, along with regulatory measures, is crucial before broader adoption [*interview*].

### Structural barriers

Innovation, according to ecosystem theory, thrives on collaboration rather than competition (Moore, 1996). This is particularly crucial in industries like fashion, where long and complex supply chains exist, making it difficult to implement changes effectively (de Jesus and Mendonça, 2018). Full digitalization of the fashion sector requires cooperation across the entire supply chain, but standardizing processes is both challenging and costly. The global and fragmented nature of the industry further complicates efforts to reach common standards, slowing down the adoption of digital technologies [*interview*]. A lack of a clear technology strategy adds to these difficulties (Chauhan et al., 2022). Innovations in the fashion ecosystem often emerge collectively, and the uncertainty surrounding their benefits can deter early adoption. Misaligned priorities and incentives across the value chain exacerbate this hesitation. For example, factories that produce for multiple brands may hesitate to invest in new technology unless all their customers align, while brands are reluctant to pay for improvements that also benefit competitors (Adner, 2017).

Data management presents another challenge. While steps are being taken in the sector[17], the absence of standardized data processes, lack of material flow data, and concerns over information security create additional obstacles to digital transformation (Chauhan et al., 2022). For digital technologies to succeed, multiple players in the supply chain must adopt the same tools. However, this can be especially difficult for retailers with many suppliers, who face a fragmented and time-consuming data integration process [*interview*]. While larger companies may drive initial adoption of digital technologies DPP, these innovations have to made available in a cost-effective way to SMEs as well [*interview 11*].

### Operational barriers

The textiles industry faces significant challenges in achieving data standardization due to its traditionally unstructured and fragmented nature, with constantly changing designs, materials, and suppliers. This lack of a structured data management process has been a major hurdle for the textiles sector (Chauhan et al., 2022). While technologies for digital prototyping exist, the optimization of workflows remains incomplete. Standardized methods for measuring and integrating textile characteristics into design

---

[17] https://unece.org/trade/traceability-sustainable-garment-and-footwear

software are absent, and software suppliers show limited interest in collaboration [*interview*]. Time constraints further complicate matters, as much of the sample preparation is done last minute, while textile digitization requires more time [*interview*]. In circular business models, such as rental services, managing the supply chain presents additional challenges, as complex operational systems must be customized for individual customers, ideally supported by large, automated systems [*interview*]. Scaling, maturing, and standardization are essential for digital solutions to significantly impact circularity. For instance, when introducing DPP, ERP systems must adopt a life-cycle perspective and integrate data effectively. However, much of the available data is scattered across emails, Excel sheets, and isolated files [*interview*]. Consequently, DPP is often seen as an expensive administrative burden [*interview*]. Finally, there is a tendency to work in silos, with departments focusing on their specific technologies rather than adopting an integrated approach [*interview*].

### Attitudinal barriers and cultural hesitance

The fashion sector faces significant risk aversion, viewing innovation as unpredictable and organic (de Jesus and Mendonça, 2018). Traditionally, it is not seen as an innovative industry, leading to resistance to change [*interviews*]. The rapid pace of digital technology development adds to this resistance, with the perceived inconvenience of adopting new technologies being a major factor (Chauhan et al., 2022). Moreover, without clear standards for which systems to adopt, companies fear committing to the wrong technology or one that may not become widely used [*interview*]. Market unpredictability, including reduced preordering, further complicates this transition, as brands demand proof of system reliability before fully committing [*interview*]. Psychological factors also play a role in this resistance. Many in the industry see design and wholesale processes as artisanal and prefer to physically handle products rather than use digital tools [*interviews*]. This is particularly true in areas like quality control, where professionals are reluctant to cede control to machines. On the consumer side, digital tools have significantly improved the convenience of circular economy models, such as second-hand fashion through e-commerce and resale platforms. However, digital solutions have yet to fully address consumer trust issues (Charnley et al., 2022). Despite these challenges, progress is being made as companies increasingly use data analytics, digital platforms, and advanced product imagery to improve customer communication and address concerns around convenience, hygiene, trust, and security.

### Policy related barriers

Absence of appropriate policy and regulations is mentioned as a barrier for implementing digital solutions (Chauhan et al., 2022) For example, to optimize production and reduce overstock, more items need to be produced closer to customers through reshoring, which shortens lead times by reducing shipping times. However, implementing reshoring in a highly competitive industry requires political decisions and significant investment [*interview*]. Brands need to be empowered to contribute effectively to these solutions, as the business case for circularity is not yet compelling.

For digitalization and circularity to succeed, there needs to be a financial incentive, and the EU could provide guidance for this transition *[interview]*. Strict enforcement will be necessary, also in the context of DPP implementation. It should be ensured that products without a DPP cannot enter the European market, thereby pressuring the value chain to comply. Nonetheless, there are concerns about how to verify the accuracy of the data provided. This will require fashion companies to make more discerning choices about their suppliers, raising the standards for all. Many industry players are delaying action until the precise requirements for DPP are clarified. If the sector focuses solely on meeting legal requirements, the impact on sustainability and circularity could be minimal *[interview]*.

### Technological barriers

Many digital technologies are still in their early stages and may not perform well or deliver high-quality results specifically for the fashion and textiles context. This leads to inertia within the industry, as many people are initially—and understandably—reluctant to adopt these digital technologies due to their current limitations and flaws. However, these technologies often improve rapidly over time. A lack of a clear technology strategy also contributes to this hesitation (Chauhan et al., 2022). For example, achieving a realistic representation of how a garment looks when worn remains a significant challenge for 3D modelling solutions *[interviews]*. Additionally, online rental platforms that use a subscription model often require customization of e-commerce platforms to accommodate recurring payments *[interview]*.

### Lack of digital skills – employee capacities

Some consider the lack of proper education on digital technologies and digital skills as the most significant barrier to digitalization in the textiles and fashion industry, especially among smaller companies and SMEs *[interview]* and among older professionals *[interview]*. The shortage of digital expertise occurs at all levels within organizations. Designers may struggle to be creative with digital design tools, while top management may fear losing control over certain processes. This contributes to a general hesitancy to fully embrace digitization *[interview]*. In addition, there is a widespread fear that automation and digitalization will lead to job losses, even though these technologies can create new opportunities in other areas [*interview]*. Digital skills and technology usage need to be consistent across the value chain; for example, using 3D models for prototyping requires suppliers to be capable of handling digital information, but generally, the technical readiness of factories remains low *[interview]*. There is a need for more focus on digital education and the inclusion of various professions, such as engineers, within the industry *[interview]*, as adopting cutting-edge technology requires significant adaptation and knowledge from employees *[interview]*.

# 4. Summary and outlook

## Summary

Between 2010 and 2022, consumption of textiles has increased significantly in the EU, with a 15 % rise in the per-person consumption. Specific categories such as footwear (+32 %), household textiles (+16 %) and other textiles (+ 48%) saw the largest increases.

Despite this consumption increase, some relative and absolute decoupling of environmental and climate pressures from consumption growth can be observed, although to a limited extent. A decrease in environmental impact intensity of textiles consumption (impact per kg of consumption) could be observed across all studied impact domains. The improvements were most significant for raw material use and greenhouse gas (GHG) emissions, where a 33 % decrease in intensity led to a net reduction in raw material use and GHG emissions per person related to textiles consumption, i.e. an “absolute” decoupling of environmental impacts from consumption volumes. In the case of water and land use, intensity improvements were lower (-14 % and - 10%) and not sufficient to make up for the consumption increase (+ 15%), resulting in a slightly higher impact per person. In these cases, only a “relative’ decoupling could be observed. Furthermore, it is difficult to assess to what extent the GHG emission reductions are due to “easy wins” and whether the decarbonisation trend will continue.

Textiles 4.0 is a potentially transformative force in the textile industry, facilitating enhanced efficiency, productivity, and market responsiveness. Digital tools such as the Internet of Things (IoT), artificial intelligence (AI), big data analytics, blockchain, and automation are already reshaping traditional business models and manufacturing processes in the textile sector. Apart from improving operations, digital technologies are also potential critical enablers of sustainability and circularity. For example, IoT and AI can help optimize supply chains by matching supply and demand more effectively, reducing waste, and fostering innovative business models like on-demand production. These technologies can allow for smarter production processes and better lifecycle management of products, potentially resulting in a lower environmental and climate impacts.

Digitalisation also offers opportunities for the efficient implementation and adoption of circular business models, for example, for supporting service-oriented, user-centred and network-based models, realizing efficiency gains and cost savings, or by creating new digital product offerings.

However, despite the potential benefits and increasing attention, implementation of digital technologies remains limited. Digitalisation is mostly incorporated by either very large companies, or very small, niche companies specialising in digital approaches. SMEs seem to fall out from this trend due to several barriers, such as the large investments required, cultural hesitance among industry practitioners, and the highly complex and fragmented nature of the textiles supply chain. Also, practice shows that sustainability objectives typically are not top of mind when companies implement them. The primary aim is mostly to improve efficiency, save costs and improve marketing and customer outreach.

While digital transformation offers new opportunities for sustainability, it also comes with potential risks and negative effects on the environment and climate, including through increased energy consumption water use associated with digital technologies. Moreover, there is a possibility that efficiency gains could further speed up the fast fashion trend and drive consumption to even higher levels, undermining efforts to promote longer product lives, reuse and reduce overconsumption.

### Outlook

*Digital technologies are expected to further transform business models*
The continued adoption of digital technologies, the development of virtual fashion, as well as the access to more data – e.g. through the implementation of the DPP - could disrupt and transform the textile industry. E-commerce is expected to increase further. Increased information availability may support the development of new business models, such as on-demand production, service-based models and prosumer-models. Relationships between buyers and suppliers are expected to change. For example, digital technologies allow for the 'direct to consumer' model in which individual designers or small brands can cut-out traditional retailers and go directly to the consumer.

Digital tools can also be effectively combined with traditional practices to boost efficiency within the sector. The application of emerging technologies can complement workers' skills (Chauhan et al., 2022). In retail, a hybrid approach, blending physical and digital experiences, could effectively merge the traditional way of working with the new possibilities offered by the digital revolution. Technological advancements and automation in production also enhance competitiveness by enabling various manufacturing steps to be relocated closer to sales markets, optimizing logistics, and improving coordination between trade and production, resulting in faster time-to-market (KPMG, 2021). Technologies like AI, blockchain, and big data may help companies meet growing demands while reducing their carbon footprint.

*Digital tools can help with transparency*
Digital technologies, such as blockchain, digital identification tags and digital product passports are considered crucial for improving the transparency and traceability of the textiles system. In this sense upcoming (DPP) regulation will make the digital transformation of the sector inevitable to some extent. By developing and implementing a reporting and verification system for material inputs and flows, as well as environmental, social and animal welfare impacts, data can be gathered for the introduction of extended producer responsibility (EPR) schemes with eco-modulated fees.

*AI is a revolutionary technology that could support the sustainability transition*
Artificial intelligence (AI) is expected to be a transformative technology with significant potential to support the sustainability goals of fashion companies. AI can enhance productivity, a critical element of a circular economy, and optimize resource use. For instance, the World Economic Forum predicts AI will play a crucial role in analysing data from satellite imagery and sensors to reduce over-irrigation in cotton farms, thereby increasing cotton yield and quality (WEF, 2021). Additionally, AI accelerates learning and scientific discovery, particularly in materials innovation, and improves customer analytics and demand forecasting, helping to reduce unnecessary stock and waste (PricewaterhouseCoopers, 2020).

*Jobs will change*
Digitalization and the use of AI will fundamentally alter job descriptions, with some roles, such as checkout personnel, likely to decline due to the rise of self-checkout and cashierless systems. However, in many areas, automation and digitalization can serve as extensions of current roles, enhancing the knowledge base of employees and facilitating various processes (KPMG, 2021). In the premium and luxury segments, manual labour may not be fully replaced (KPMG, 2021). Firms that embrace digital transformation risk making their workforce's skills obsolete due to the shift towards more complex, digitally-based tasks, leading to skill mismatches and shortages (Casciani et al., 2022). On the positive side, digital fashion companies are creating new roles and job profiles, such as digital tailors and AR/VR/MR experts, contributing to social and economic sustainability (Casciani et al., 2022).

*The global dimension*
However, implementing these solutions globally presents challenges, especially in low- and middle-income countries where many people rely on the fashion industry for their livelihoods. Additionally, the

waste and pollution associated with the sector disproportionately affect these regions. As the fashion industry evolves and digital transformation accelerates, it should be ensured that digital solutions are implemented in support of circular and sustainable practices, instead of employing the realized efficiency gains to fuel ultra-fast fashion and encourage even faster changing trends and more overconsumption.

*Will digital technology bring back jobs to Europe?*

Some experts believe that digital technologies can potentially initiate a digital reshoring of a part of textiles production to Europe [*interview*]. However, it is deemed unlikely that such new plants in Europe will be very large garment manufacturing plants. Instead, they may be very small, highly automated and digitally integrated factories which can do repair and small scale or customised production very fast, focused on specifics. Hopefully creating better quality textile jobs. Such a local production system would enable easier circularity with production and recycling close to each other. Still, it is highly uncertain whether such a reshoring will really materialise.

*Regulation is needed to drive positive outcomes*

Regulation is an important driver of the digital transformation of the textiles system. Several recent and upcoming regulatory requirements, such as the CSR Directive, due diligence rules, digital product passports and a better substantiation of green claims will drive companies to adopt digital technologies, enabling them to track and trace emissions, environmental and social impacts and resource utilization. As knowledge improves, also optimization is possible, reducing waste and solving inefficiencies.

## References

Adner, R., 2017, ‘Ecosystem as Structure: An Actionable Construct for Strategy’, *Journal of Management* 43(1), pp. 39-58 (DOI: 10.1177/0149206316678451).

Ahmad, S., et al., 2020, ‘Towards Sustainable Textile and Apparel Industry: Exploring the Role of Business Intelligence Systems in the Era of Industry 4.0’, *Sustainability* 12(7), p. 2632 (DOI: 10.3390/su12072632).

Akhtar, W. H., et al., 2022, ‘A New Perspective on the Textile and Apparel Industry in the Digital Transformation Era’, *Textiles* 2(4), pp. 633-656 (DOI: 10.3390/textiles2040037).

Alves, L., et al., 2022, ‘Towards circular economy in the textiles and clothing value chain through blockchain technology and IoT: A review - Luís Alves, Estrela Ferreira Cruz, Sérgio I Lopes, Pedro M Faria, António Miguel Rosado da Cruz, 2022’, *Waste Management & Research: The Journal for a Sustainable Circular Economy* 40(1) (DOI: 10.1177/0734242X211052858).

Amasawa, E., et al., 2023, ‘Can rental platforms contribute to more sustainable fashion consumption? Evidence from a mixed-method study’, *Cleaner and Responsible Consumption* 8, p. 100103 (DOI: 10.1016/j.clrc.2023.100103).

Antikainen, M., et al., 2018, ‘Digitalisation as an Enabler of Circular Economy’, *Procedia CIRP* 73, pp. 45-49 (DOI: 10.1016/j.procir.2018.04.027).

Arillo García, A., 2023, *Disclosing the rise of Digital Fashion: its role on Circular Economy and Sustainable Practices.*, Aalto University (https://www.studocu.com/fi/document/aalto-yliopisto/sustainable-fashion-and-textile-design/disclosing-the-rise-of-digital-fashion-its-role-on-circular-economy-and-sustainable-practices/74345531) accessed 13 June 2024.

Arrigo, E., 2021, ‘Digital platforms in fashion rental: a business model analysis’, *Journal of Fashion Marketing and Management: An International Journal* 26(1), pp. 1-20 (DOI: 10.1108/JFMM-03-2020-0044).

Avery Dennison and TEXAID, 2024, *Accelerating Textile Recycling with Digital IDs* (https://rfid.averydennison.cn/content/dam/rfid/en/news-and-insights/insights/white-papers/Accelerating-Textile-Recycling-with-Digital-IDs.pdf) accessed 29 March 2024.

Björninen, T., et al., 2014, ‘Impact of recurrent washing on the performance of electro-textile UHF RFID tags’, conference paper presented at: 2014 IEEE RFID Technology and Applications Conference (RFID-TA), September 2014.

Bocken, N. M. P., et al., 2014, ‘A literature and practice review to develop sustainable business model archetypes’, *Journal of Cleaner Production* 65, pp. 42-56 (DOI: 10.1016/j.jclepro.2013.11.039).

Bonifazi, G., et al., 2022, ‘End-of-Life Textile Recognition in a Circular Economy Perspective: A Methodological Approach Based on Near Infrared Spectroscopy’, *Sustainability* 14(16), p. 10249 (DOI: 10.3390/su141610249).

Boston Consulting Group, 2022, *Metaverse and sustainability in fashion. opportunity or threat?* (https://web-assets.bcg.com/1e/23/d9e9792a4988b61e708794baa174/bcg-sustainability-metaverse-in-fashion-opportunity-or-threat-oct-2022.pdf) accessed 12 June 2024.

Böttcher, T. P., et al., 2023, 'Digital sustainable business models: Using digital technology to integrate ecological sustainability into the core of business models', *Information Systems Journal* n/a(n/a), pp. 1-26 (DOI: 10.1111/isj.12436).

Bressanelli, G., et al., 2018, 'Exploring How Usage-Focused Business Models Enable Circular Economy through Digital Technologies', *Sustainability* 10(3), p. 639 (DOI: 10.3390/su10030639).

Broccardo, L., et al., 2023, 'How digitalization supports a sustainable business model: A literature review', *Technological Forecasting and Social Change* 187, p. 122146 (DOI: 10.1016/j.techfore.2022.122146).

Carrara, S., et al., 2023, *Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study*, No JRC132889, Publications Office of the European Union, Luxembourg (https://publications.jrc.ec.europa.eu/repository/handle/JRC132889).

Casciani, D., et al., 2022, 'Exploring the nature of digital transformation in the fashion industry: opportunities for supply chains, business models, and sustainability-oriented innovations', *Sustainability: Science, Practice and Policy* 18(1), pp. 773-795 (DOI: 10.1080/15487733.2022.2125640).

Chapagain, A. K., et al., 2006, 'The water footprint of cotton consumption: An assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries', *Ecological Economics* 60(1), pp. 186-203 (DOI: 10.1016/j.ecolecon.2005.11.027).

Charnley, F., et al., 2022, 'Can Digital Technologies Increase Consumer Acceptance of Circular Business Models? The Case of Second Hand Fashion', *Sustainability* 14(8), p. 4589 (DOI: https://doi.org/10.3390/su14084589).

Chauhan, C., et al., 2022, 'Linking circular economy and digitalisation technologies: A systematic literature review of past achievements and future promises', *Technological Forecasting and Social Change* 177, p. 121508 (DOI: 10.1016/j.techfore.2022.121508).

Cobbing, M., et al., 2024, *Taking the Shine off SHEIN: A business model based on hazardous chemicals and environmental destruction*, Greenpeace Germany (https://www.greenpeace.de/publikationen/S04261_Konsumwende_StudieEN_Mehr%20Schein_v9.pdf) accessed 4 December 2024.

Coscieme, L., et al., 2022, 'A framework of circular business models for fashion and textiles: the role of business-model, technical, and social innovation', *Sustainability: Science, Practice and Policy* 18(1), pp. 451-462 (DOI: 10.1080/15487733.2022.2083792).

Davies, I. A. and Doherty, B., 2019, 'Balancing a Hybrid Business Model: The Search for Equilibrium at Cafédirect', *Journal of Business Ethics* 157(4), pp. 1043-1066 (DOI: 10.1007/s10551-018-3960-9).

de Jesus, A. and Mendonça, S., 2018, 'Lost in Transition? Drivers and Barriers in the Eco-innovation Road to the Circular Economy', *Ecological Economics* 145, pp. 75-89 (DOI: 10.1016/j.ecolecon.2017.08.001).

EEA, 2019, *Textiles in Europe's circular economy*, Briefing (https://www.eea.europa.eu/publications/textiles-in-europes-circular-economy/textiles-in-europe-s-circular-economy) accessed 20 September 2024.

EEA, 2021, *A framework for enabling circular business models in Europe*, Publication, European Environment Agency, Copenhagen, Denmark (https://www.eea.europa.eu/publications/a-framework-for-enabling-circular) accessed 20 September 2024.

EEA, 2022, *Textiles and the environment: the role of design in Europe's circular economy*, Briefing, European Environment Agency, Copenhagen, Denmark (https://www.eea.europa.eu/publications/textiles-and-the-environment-the/textiles-and-the-environment-the) accessed 17 October 2024.

EEA, 2023, 'EU exports of used textiles in Europe's circular economy', European Environment Agency (https://www.eea.europa.eu/publications/eu-exports-of-used-textiles/eu-exports-of-used-textiles) accessed 29 July 2024.

EEA, 2024, *The destruction of returned and unsold textiles in Europe's circular economy*, Briefing, European Environment Agency, Copenhagen  Denmark (https://www.eea.europa.eu/publications/the-destruction-of-returned-and/the-destruction-of-returned-and) accessed 20 September 2024.

ETC CE, 2023, *EU exports of used textiles in Europe's circular economy*, Eionet Report ETC/CE No 2023/4, European Topic Centre Circular Economy and Resource Use (https://www.eionet.europa.eu/etcs/etc-ce/products/etc-ce-report-2023-4-eu-exports-of-used-textiles-in-europe2019s-circular-economy) accessed 12 April 2023.

ETC WMGE, 2019, *Textiles and the environment in a circular economy*, ETC WMGE Report No 6/2019 (https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/textiles-and-the-environment-in-a-circular-economy) accessed 20 September 2024.

ETC/CE, 2022, *Textiles and the Environment - The role of design in Europe's circular economy*, No ETC/CE Report 2/2022, European Topic Centre Circular Economy and Resource Use (https://www.eionet.europa.eu/etcs/etc-ce/products/etc-ce-products/etc-ce-report-2-2022-textiles-and-the-environment-the-role-of-design-in-europes-circular-economy) accessed 29 August 2024.

ETC/CE, 2023, 'EU exports of used textiles in Europe's circular economy', Eionet Portal (https://www.eionet.europa.eu/etcs/etc-ce/products/etc-ce-report-2023-4-eu-exports-of-used-textiles-in-europe2019s-circular-economy) accessed 29 July 2024.

ETC/CE, 2024a, *Volumes and destruction of returned and unsold textiles in Europe's circular economy*, Eionet Report ETC/CE No 2024/4.

ETC/CE, 2024b, *Volumes and destruction of returned and unsold textiles in Europe's circular economy*, ETC CE Report No 4, European Environment Agency (EEA), Copenhagen (https://www.eionet.europa.eu/etcs/etc-ce/products/etc-ce-report-2024-4-volumes-and-destruction-of-returned-and-unsold-textiles-in-europes-circular-economy) accessed 25 June 2024.

ETC/WMGE, 2019, *Textiles and the environment in a circular economy*, Eionet Report No 6/2019, European Topic Centre for Waste and Materials in a Green Economy (https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-reports/textiles-and-the-environment-in-a-circular-economy) accessed 26 March 2020.

ETC/WMGE, 2021, *Business Models in a Circular Economy*, No 2, European Environment Agency (EEA), Copenhagen (https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/business-models-in-a-circular-economy) accessed 19 June 2024.

EU Blockchain Observatory and Forum, 2023, *Trend Report - Ethereum Merge*, European Commission (https://blockchain-observatory.ec.europa.eu/publications/trend-report-ethereum-merge_en) accessed 17 December 2024.

Eunomia, 2022, *Driving a Circular Economy for Textiles through EPR* (https://eeb.org/wp-content/uploads/2022/03/CE-Textiles-EPR.pdf) accessed 12 June 2024.

Euratex, 2021, ‘2021 must be a turning point for the European textiles and clothing industry’, European Apparel and Textile Confederation (https://euratex.eu/news/2021-must-be-a-turning-point-for-the-european-textiles-and-clothing-industry/) accessed 28 September 2021.

EURATEX, 2023a, *Facts  Key figures 2022 of the European Textile and clothing industry* (https://euratex.eu/wp-content/uploads/EURATEX_FactsKey_Figures_2022rev-1.pdf) accessed 20 September 2024.

EURATEX, 2023b, STEP2030 Manifesto, (https://euratex.eu/wp-content/uploads/STEP2030-Manifesto_final_evaluated-10.07.23.pdf) accessed 29 March 2024.

EURATEX, 2024, *Facts & Key Figures 2024 of the European Textile and Clothing Industry* (https://euratex.eu/wp-content/uploads/EURATEX-Facts-Key-Figures-2024.pdf) accessed 29 August 2024.

European Commission, 2022, EU strategy for sustainable and circular textiles (COM(2022) 141 final).

European Commission, 2024a, ‘Ecodesign for Sustainable Products Regulation’ (https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en) accessed 28 August 2024.

European Commission, 2024b, ‘Press Releasse: Commission opens formal proceedings against Temu under DSA’, European Commission (https://ec.europa.eu/commission/presscorner/detail/en/ip_24_5622) accessed 2 December 2024.

European Commission, 2025, A Competitiveness Compass for the EU (COM(2025) 30 final).

Eurostat, 2023, ‘E-commerce continues to grow in the EU’, 28 February 2023 (https://ec.europa.eu/eurostat/web/products-eurostat-news/w/DDN-20230228-2) accessed 20 September 2024.

Farfan, J. and Lohrmann, A., 2023, ‘Gone with the clouds: Estimating the electricity and water footprint of digital data services in Europe’, *Energy Conversion and Management* 290, p. 117225 (DOI: 10.1016/j.enconman.2023.117225).

Fernández-Caramés, T. M. and Fraga-Lamas, P., 2018, ‘Towards The Internet of Smart Clothing: A Review on IoT Wearables and Garments for Creating Intelligent Connected E-Textiles’, *Electronics* 7(12), p. 405 (DOI: 10.3390/electronics7120405).

Geissdoerfer, M., et al., 2018, ‘Sustainable business model innovation: A review’, *Journal of Cleaner Production* 198, pp. 401-416 (DOI: 10.1016/j.jclepro.2018.06.240).

Ghoreishi, M. and Happonen, A., 2022, ‘The Case of Fabric and Textile Industry: The Emerging Role of Digitalization, Internet-of-Things and Industry 4.0 for Circularity’, Proceedings of Sixth International Congress on Information and Communication Technology, Singapore, 2022.

Gür, U., 2023, ‘Smart Product-Service Systems in Fashion Industry: A Systematic Review of Sustainability Results’, *Journal of Productivity* 57(4), pp. 747-760 (DOI: https://doi.org/10.51551/verimlilik.1220774).

Hossain, M. K., et al., 2024, ‘Adoption of artificial intelligence and big data analytics: an organizational readiness perspective of the textile and garment industry in Bangladesh’, *Business Process Management Journal* 30(7), pp. 2665-2683 (DOI: 10.1108/BPMJ-11-2023-0914).

Hund, K., et al., 2023, *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition*,.

Huygens, D., et al., 2023, *Techno-scientific assessment of the management options for used and waste textiles in the European Union* (https://publications.jrc.ec.europa.eu/repository/handle/JRC134586) accessed 9 December 2024.

IEA, 2023, *Critical Minerals Market Review 2023*, IEA, Paris (https://www.iea.org/reports/critical-minerals-market-review-2023).

IEA, 2024, *Electricity 2024: Analysis and Forecast to 2026*, IEA, Paris (https://www.iea.org/reports/electricity-2024).

Izsak, K. and Moreno, C., 2024, *Monitoring the twin transition of industrial ecosystems: textiles : analytical report*, Publications Office of the European Union, Luxembourg (https://data.europa.eu/doi/10.2826/308561) accessed 10 March 2025.

Justice et Paix, 2019, *Les fausses promesses du numérique: Environnement, éducation, santé, travail*, Commission Justice et Paix francophone de Belgique, Brussels.

Keefe, E. M., et al., 2022, 'Textile additive manufacturing: An overview' Dinh Duc, N. (ed.), *Cogent Engineering* 9(1), p. 2048439 (DOI: 10.1080/23311916.2022.2048439).

Köhler, A. R., et al., 2011, 'Prospective Impacts of Electronic Textiles on Recycling and Disposal', *Journal of Industrial Ecology* 15(4), pp. 496-511 (DOI: 10.1111/j.1530-9290.2011.00358.x).

KPMG, 2021, *Front row: Seeing the fashions of the future - Fashion 2030 study* (https://assets.kpmg.com/content/dam/kpmg/ie/pdf/2021/05/ie-front-row-seeing-fashions-future.pdf) accessed 12 June 2024.

Kristoffersen, E., et al., 2020, 'The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies', *Journal of Business Research* 120, pp. 241-261 (DOI: 10.1016/j.jbusres.2020.07.044).

KU Leuven, 2022, *Metals for Clean Energy: Pathways to solving Europe's raw materials challenge*, Eurometaux, Leuven.

Landmark, A. D. and Sjøbakk, B., 2017, 'Tracking customer behaviour in fashion retail using RFID', *International Journal of Retail & Distribution Management* 45(7/8), pp. 844-858 (DOI: 10.1108/IJRDM-10-2016-0174).

Le Monde, 2024, 'Shein and Temu products found to contain high levels of toxic chemicals', 14 August 2024 (https://www.lemonde.fr/en/international/article/2024/08/14/shein-and-temu-products-found-to-contain-high-levels-of-toxic-chemicals_6715032_4.html) accessed 4 December 2024.

Li, P., et al., 2023, 'Making AI Less "Thirsty": Uncovering and Addressing the Secret Water Footprint of AI Models', arXiv (http://arxiv.org/abs/2304.03271) accessed 5 December 2024.

Malmodin, J., et al., 2024, 'ICT sector electricity consumption and greenhouse gas emissions – 2020 outcome', *Telecommunications Policy* 48(3), p. 102701 (DOI: 10.1016/j.telpol.2023.102701).

Martinez-Jaramillo, J. E. and Tilebein, M., 2024, 'A fix that may fail: A qualitative model to explore potential rebound effects of digital textile microfactories', *Systems Research and Behavioral Science*, p. sres.3043 (DOI: 10.1002/sres.3043).

McKinsey & Company and BOF Insights, 2024, *The State of Fashion 2025*, No 9 (https://www.mckinsey.com/industries/retail/our-insights/state-of-fashion) accessed 14 March 2025.

Miller, R. E. and Blair, P. D., 2009, *Input output analysis foundations and extensions*, Cambridge University Press, Cambridge, UK.

Moore, J. F., 1996, *The death of competition : leadership and strategy in the age of business ecosystems*,.

Niinimäki, K., et al., 2023, *How data can enhance  circular economy of textiles: From knowledge and system understanding to actions*, Aalto University (https://aaltodoc.aalto.fi/server/api/core/bitstreams/ee419a83-2cdc-4f63-bfcc-d1befa8c0eb4/content) accessed 29 March 2024.

Osterwalder, A. and Pigneur, Y., 2010, *Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers*, Wiley.

Pous, R., et al., 2023, 'Showing products in a retail store digital twin with item location captured by an RFID robot', conference paper presented at: 2023 IEEE 13th International Conference on RFID Technology and Applications (RFID-TA), September 2023.

PricewaterhouseCoopers, 2020, 'Future-proofing sustainable fashion via digitalisation and transparency', PwC (https://www.pwc.nl/en/insights-and-publications/services-and-industries/retail-and-consumer-goods/future-proofing-sustainable-fashion-via-digitalisation-and-trans.html) accessed 29 January 2024.

Rantala, T., et al., 2023, *Digital technologies for circular manufacturing*, VTT White Paper Vol. 2023, VTT Technical Research Centre of Finland (https://cris.vtt.fi/ws/portalfiles/portal/76497949/Digital_technologies_for_circular_manufacturing_white_paper.pdf) accessed 30 January 2024.

Roichman, R., et al., 2024, 'The convenience economy: Product flows and GHG emissions of returned apparel in the EU', *Resources, Conservation and Recycling* 210, p. 107811 (DOI: 10.1016/j.resconrec.2024.107811).

Saccani, N., et al., 2023, 'Circular supply chain orchestration to overcome Circular Economy challenges: An empirical investigation in the textile and fashion industries', *Sustainable Production and Consumption* 35, pp. 469-482 (DOI: 10.1016/j.spc.2022.11.020).

Singh, J., et al., 2019, 'Challenges and opportunities for scaling up upcycling businesses – The case of textile and wood upcycling businesses in the UK', *Resources, Conservation and Recycling* 150, p. 104439 (DOI: 10.1016/j.resconrec.2019.104439).

Stadler, K., et al., 2018, 'Exiobase 3: developing a time series of detailed environmentally extended multi-regional input-output tables', *Journal of Industrial Ecology* 22(3), pp. 502-515 (DOI: https://doi.org/10.1111/jiec.12715).

United Nations Conference on Trade and Development (UNCTAD), U. N., 2024, *Digital Economy Report 2024 Shaping an Environmentally Sustainable and Inclusive Digital Future*, International Trade Centre, Bloomfield.

Vellanki, D. and Gopinath, J., 2023, *Connecting Threads: Assessing Digital Solutions and Needs for Circular Textiles*, White paper, T-REX Project (https://trexproject.eu/wp-content/uploads/2023/11/Connecting-Threads-Assessing-Digital-Solutions-and-Needs-for-Circular-Textiles-T-REX-Project-White-Paper.pdf) accessed 29 March 2024.

WEF, 2021, ‘How AI can help water go further in farming’, World Economic Forum (https://www.weforum.org/stories/2021/01/ai-agriculture-water-irrigation-farming/) accessed 5 December 2024.

Wiegand, T. and Wynn, M., 2023, ‘Sustainability, the Circular Economy and Digitalisation in the German Textile and Clothing Industry’, *Sustainability* 15(11), p. 9111 (DOI: 10.3390/su15119111).

Wojnowska-Baryła, I., et al., 2024, ‘The Growing Problem of Textile Waste Generation—The Current State of Textile Waste Management’, *Energies* 17(7), p. 1528 (DOI: 10.3390/en17071528).

Wynn, M. and Jones, P., 2022, ‘Digital Technology Deployment and the Circular Economy’, *Sustainability* 14(15), p. 9077 (DOI: 10.3390/su14159077).

Xu, B., et al., 2022, ‘Current Situation and Construction of Recycling System in China for Post-Consumer Textile Waste’, *Sustainability* 14(24), p. 16635 (DOI: 10.3390/su142416635).

# Annexes

## Annex 1: Definition of textile products

| **Product type** | |
|---|---|
| Textile products | included are CPA 2.1 Product groups 13.91, 13.92, 13.93, 13.94, 13.95, 13.96, 13.99, 14.11, 14.12, 14.13, 14.14, 14.19, 14.2, 14.31, 14.32 and 15.2 (footwear). |
| Carpets | refers to product group 13.93 'Carpets and rugs' |
| Household textiles | refers to product group 13.92 'Made-up textile articles, except apparel', which consists of blankets, including travelling rugs; bed, table, toilet or kitchen linen; quilts, eiderdowns, cushions, pouffes, pillows, sleeping bags etc.; curtains, valances, blinds, bedspreads, furniture or machine covers etc.; tarpaulins, tents, camping goods, sails, sunblinds, loose covers for cars, machines or furniture etc.; flags, banners, pennants etc.; dust cloths, dishcloths and similar articles, life jackets, parachutes etc. Note: facemasks and articles for face protection are also part of class 13.92. |
| Other textiles | refers to product groups 13.91 (knitted and crocheted fabrics), 13.94 (cordage, rope, twinage and netting), 13.95 (Non-wovens and articles made from non-wovens, except apparel), 13.96 (Other technical and industrial textiles) and 13.99 Other (textiles n.e.c.). |
| Clothing | refers to product groups 14.11 (Articles of fur); 14.2 (Leather clothes); 14.12 (Workwear), 14.13 (Other outerwear), 14.14 (Underwear), 14.19 (Other wearing apparel and accessories), 14.31 (Knitted and crocheted apparel), 14.32 (Other knitted and crocheted apparel) |

## Annex 2: Modelling methodology

The global distribution of pressures and effects related to final the consumption of textile products have been calculated using the ESTAT FIGARO (edition 2024, timeseries 2010-2022) multiregional input output model. The FIGARO model includes the EU inter-country supply, use and input-output tables (developed by Eurostat and the JRC) are part of official EU statistics (2000-2022 data). The FIGARO tables are benchmarked against the most recent macroeconomic aggregates and respect the same quality standards as official statistics and are released annually by Eurostat (T-2). The tables present the relationship between the EU27 and 18 non-EU countries plus a rest of world region, covering 64 industries (NACE rev.2 classification).

The available extension data in FIGARO are from the ESTAT Air Emissions Accounts. Air emission accounts are compiled according to the system of environmental economic accounting and can therefore be readily combined with input-output tables for further analysis. The data on employment for each EU Member State at the level of 64 industries (based on NACE Rev. 2) are expressed in numbers of persons employed. These data are collected via the European system of accounts (ESA 2010) transmission programme and are available on Eurostat's website [nama_10_a64_e]. Note: These data sources are restricted to EU27 data (and in addition UK-data), but do not cover data for non-EU countries. We completed the environmental extensions to the timeseries model based on EXIOBASE v.3.8.2[18] data (Stadler et al., 2018) and ESTAT Air Emissions Accounts (AEA) by NACE Rev. 2 activity. The calculation started from the following identities:

---

[18] 10.5281/zenodo.3583070

$$x = A \cdot x + y \quad (1)$$

where *x* is the total output vector, *A* the matrix of direct input coefficients (or matrix of technological coefficients), and *y* is the final demand vector. Solving the model for output gives (Miller and Blair, 2009)::

$$x = (I - A)^{-1} \cdot y = L \cdot y \qquad (2)$$

where *I* is the identity matrix, and *L* the Leontief inverse also known as the multiplier matrix or matrix of direct and indirect output requirements per unit produced for final demand. The Leontief model implies the following assumptions: prices are fixed in the short term, input coefficients are constant regardless of output or final demand level changes, structure of the economy is taken to be constant, at least in the reported period.

The direct environmental effects of production activities are the result of the sum of the direct effects associated with each unit produced in each industry:

$$e^T = \sum_1^n e_i = \sum_1^n e_i^{int} \cdot x_n = < e^{int} > \cdot\, x \qquad (3)$$

By multiplying the environmental pressure per output unit (measured in physical units per Euro worth of output) by the total output of each industry (measured in Euro), defined by equation (2), an environmentally extended input-output model is created:

$$e^T =< e^{int} > \cdot\, x =< e^{int} > \cdot\, (I - A)^{-1} \cdot y \qquad (3)$$

where $e^T$ is the vector of total environmental pressures associated with the corresponding amounts of the products groups finally used (vector *y*) and $e^{int}$ the environmental pressure intensity vector. Each element of $e^{int}$ represents the amount of the environmental pressure directly caused by the production of a product group. Each element of $e^{int}$ in the FIAGRO model is allocated to a region, which allows to derive the EU27 share of generated gross value added, employment, raw material use, water use, land use and greenhouse gas emissions in the total footprint.

While previous results reporting on the role of EU27 textile consumption in global environmental impacts were based on EXIOBASE (update was based on a modified version of EXIOBASE v3.8.1), this report makes use of the ESTAT FIGARO tables. Both the improved quality of the FIGARO model and its annual updates make together that the choice for this model is well-founded. However, the shift to this model does have an impact on the comparison of the results of this study with previous studies. Numerous changes complicate a precise description of the changes and comparability between results. However, the differences in the allocation of final demand into consumption domains, of which textiles is one, has a major impact on the results. In calculating the impacts of the consumption domain of textiles (and other consumption domains), the methodology includes an allocation of final demand from household into different consumption domains. In this allocation step, the output of sectors is attributed to one (or multiple) consumption domains. In using EXIOBASE the allocation table included the attribution of 163 industry outputs to 12 consumption domains, while in using FIGARO the allocation table included the attribution of 64 industry outputs to 12 consumption domains. In dialogue with EEA, a 'new' allocation table is developed for FIGARO.

## Table 1: Allocation table of sectoral output (FIGARO NACE Rev.2 classification) to consumption domains.

| FIG_industry code | FIG_industry description | Food | Housing, water, electricity, gas and other fuels | Clothing, footwear, household textiles | Personal mobility | Household equipment and routine household | Miscellaneous goods and services | Beverages | Recreation and culture | Restaurants and hotels | Health | Communication | Education |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A01 | Crop and animal production, hunting and related service activities | 0.96 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| A02 | Forestry and logging | 0.02 | 0.72 | 0.25 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| A03 | Fishing and aquaculture | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| B | Mining and quarrying | 0.47 | 0.44 | 0.00 | 0.09 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C10T12 | Manufacture of food products; beverages and tobacco products | 0.83 | 0.00 | 0.00 | 0.00 | 0.00 | 0.08 | 0.08 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C13T15 | Manufacture of textiles, wearing apparel, leather and related products | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C16 | Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials | 0.01 | 0.86 | 0.13 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C17 | Manufacture of paper and paper products | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C18 | Printing and reproduction of recorded media | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C19 | Manufacture of coke and refined petroleum products | 0.00 | 0.30 | 0.00 | 0.71 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C20 | Manufacture of chemicals and chemical products | 0.00 | 0.32 | 0.10 | 0.01 | 0.01 | 0.02 | 0.00 | 0.45 | 0.00 | 0.03 | 0.06 | 0.00 |
| C21 | Manufacture of basic pharmaceutical products and pharmaceutical preparations | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 |
| C22 | Manufacture of rubber and plastic products | 0.00 | 0.67 | 0.21 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.12 | 0.00 |
| C23 | Manufacture of other non-metallic mineral products | 0.00 | 0.79 | 0.21 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C24 | Manufacture of basic metals | 0.00 | 0.93 | 0.00 | 0.00 | 0.07 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C25 | Manufacture of fabricated metal products, except machinery and equipment | 0.00 | 0.36 | 0.00 | 0.00 | 0.16 | 0.00 | 0.00 | 0.48 | 0.00 | 0.00 | 0.00 | 0.00 |
| C26 | Manufacture of computer, electronic and optical products | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.71 | 0.00 | 0.30 | 0.00 | 0.00 |
| C27 | Manufacture of electrical equipment | 0.00 | 0.00 | 0.00 | 0.04 | 0.94 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 |
| C28 | Manufacture of machinery and equipment n.e.c. | 0.00 | 0.04 | 0.00 | 0.00 | 0.44 | 0.00 | 0.00 | 0.53 | 0.00 | 0.00 | 0.00 | 0.00 |
| C29 | Manufacture of motor vehicles, trailers and semi-trailers | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C30 | Manufacture of other transport equipment | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C31_32 | Manufacture of furniture; | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | other manufacturing | | | | | | | | | | | | |
| C33 | Repair and installation of machinery and equipment | 0.00 | 0.07 | 0.17 | 0.01 | 0.26 | 0.00 | 0.00 | 0.46 | 0.00 | 0.05 | 0.00 | 0.00 |
| D35 | Electricity, gas, steam and air conditioning supply | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| E36 | Water collection, treatment and supply | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| E37T39 | Sewerage, waste management, remediation activities | 0.00 | 0.95 | 0.00 | 0.00 | 0.00 | 0.00 | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| F | Construction | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| G45 | Wholesale and retail trade and repair of motor vehicles and motorcycles | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| G46 | Wholesale trade, except of motor vehicles and motorcycles | 0.15 | 0.32 | 0.07 | 0.12 | 0.02 | 0.11 | 0.01 | 0.07 | 0.05 | 0.04 | 0.03 | 0.01 |
| G47 | Retail trade, except of motor vehicles and motorcycles | 0.15 | 0.32 | 0.07 | 0.12 | 0.02 | 0.11 | 0.01 | 0.07 | 0.05 | 0.04 | 0.03 | 0.01 |
| H49 | Land transport and transport via pipelines | 0.17 | 0.13 | 0.08 | 0.44 | 0.01 | 0.03 | 0.01 | 0.06 | 0.00 | 0.03 | 0.04 | 0.00 |
| H50 | Water transport | 0.26 | 0.20 | 0.12 | 0.17 | 0.02 | 0.04 | 0.02 | 0.08 | 0.00 | 0.05 | 0.05 | 0.00 |
| H51 | Air transport | 0.26 | 0.20 | 0.12 | 0.17 | 0.02 | 0.04 | 0.02 | 0.08 | 0.00 | 0.05 | 0.05 | 0.00 |
| H52 | Warehousing and support activities for transportation | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| H53 | Postal and courier activities | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 |
| I | Accommodation and food service activities | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 |
| J58 | Publishing activities | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| J59_60 | Motion picture, video, television programme production, programming and broadcasting activities | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| J61 | Telecommunications | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 |
| J62_63 | Computer programming, consultancy, and information service activities | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| K64 | Financial service activities, except insurance and pension funding | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| K65 | Insurance, reinsurance and pension funding, except compulsory social security | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| K66 | Activities auxiliary to financial services and insurance activities | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| L | Real estate activities | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| M69_70 | Legal and accounting activities, activities of head offices, management consultancy activities | 0.00 | 0.43 | 0.00 | 0.00 | 0.00 | 0.24 | 0.00 | 0.33 | 0.00 | 0.00 | 0.00 | 0.00 |
| M71 | Architectural and engineering activities, technical testing and analysis | 0.00 | 0.43 | 0.00 | 0.00 | 0.00 | 0.24 | 0.00 | 0.33 | 0.00 | 0.00 | 0.00 | 0.00 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M72 | Scientific research and development | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| M73 | Advertising and market research | 0.00 | 0.43 | 0.00 | 0.00 | 0.00 | 0.24 | 0.00 | 0.33 | 0.00 | 0.00 | 0.00 | 0.00 |
| M74_75 | Other professional, scientific and technical activities, veterinary activities | 0.00 | 0.43 | 0.00 | 0.00 | 0.00 | 0.24 | 0.00 | 0.33 | 0.00 | 0.00 | 0.00 | 0.00 |
| N77 | Rental and leasing activities | 0.00 | 0.00 | 0.00 | 0.00 | 0.52 | 0.00 | 0.00 | 0.31 | 0.00 | 0.00 | 0.17 | 0.00 |
| N78 | Employment activities | 0.00 | 0.43 | 0.00 | 0.00 | 0.00 | 0.24 | 0.00 | 0.33 | 0.00 | 0.00 | 0.00 | 0.00 |
| N79 | Travel agency, tour operator reservation service and related activities | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| N80T82 | Security and investigation, service and landscape, office administrative and support activities | 0.00 | 0.43 | 0.00 | 0.00 | 0.00 | 0.24 | 0.00 | 0.33 | 0.00 | 0.00 | 0.00 | 0.00 |
| O84 | Public administration and defence; compulsory social security | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.99 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| P85 | Education | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 |
| Q86 | Human health activities | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 |
| Q87_88 | Residential care activities and social work activities without accommodation | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 |
| R90T92 | Creative, arts and entertainment activities, libraries, archives, museums and other cultural activities, gambling and | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | betting activities | | | | | | | | | | | | |
| R93 | Sports activities and amusement and recreation activities | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| S94 | Activities of membership organisations | 0.00 | 0.50 | 0.00 | 0.00 | 0.00 | 0.20 | 0.00 | 0.30 | 0.00 | 0.00 | 0.00 | 0.00 |
| S95 | Repair of computers and personal and household goods | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| S96 | Other personal service activities | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| T | Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| U | Activities of extraterritorial organisations and bodies | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

## Annex 3: Glossary of Digital Technologies and their application in textiles

| | |
|---|---|
| **3D modelling** | Designing and/or prototyping in 3D, zero-waste patternmaking |
| **3D knitting** | 3D knitting is an additive manufacturing technique that uses computerized knitting machines to create seamless, three-dimensional garments or fabrics directly from yarn, without the need for cutting or sewing multiple fabric pieces together. |
| **3D printing** | See ‘additive manufacturing’ |
| **Additive manufacturing** | Additive manufacturing, or 3D printing, is a computer-controlled manufacturing technology that builds up objects by depositing materials in layers. It offers flexibility in design and uses fewer resources than conventional manufacturing processes, resulting in reduced operational costs and less waste. It allows the rapid manufacturing of products on-demand, in low volumes and with complex geometries. In textiles, it is typically used to rapidly create prototypes of newly designed products (Keefe et al., 2022). |
| **Artificial Intelligence (AI)** | Artificial Intelligence (AI) are computer systems that can simulate human intelligence in decision making (Rantala et al., 2023). In textiles, AI is used for decision support, to enhance design, production, and quality control processes. It can predict fashion trends, optimize fabric cutting for minimal |

| | |
|---|---|
| | waste, detect defects in real-time, and improve supply chain efficiency by automating inventory management. |
| **Augmented Reality (AR)** | In AR, the user can look around to see what is going on in the machines around him/her, whereas in VR, the user can teleport to other locations in the factory, without having to walk there (Rantala et al., 2023). |
| **Big data** | The application of digital technologies, such as RFID, sensors, cloud technology and IoT generates enormous amounts of different datasets. 'Big data' refers to the heterogenous nature of these datasets and the technologies used to integrate and analyse these diverse data into information and insights for decision-making. Also the circular economy can benefit from big data and analytics by generating sustainability insights that can be fed into decision-making processes to enhance product life cycles (Bressanelli et al., 2018; Ahmad et al., 2020). |
| **Blockchain** | Blockchain provides immutable shared data records and well-documented data management processes (Rantala et al., 2023), which support transparency and traceability across the textiles value chain (Alves et al., 2022). For example, through blockchain, information about material origins can be shared and transaction information can be stored. |
| **Cloud computing** | Cloud computing is the delivery of computing services, such as server capacity, storage, databases, software, analytics and intelligence, over the internet ("the cloud"), enabling the textiles industry to adopt innovative technologies at a low cost. It also supports the distributed production model of the textiles sector, allowing the operation, optimisation and monitoring of different plants from anywhere through IoT and cloud technology (Ahmad et al., 2020). |
| **Computer-aided design (CAD)** | Computer-Aided Design (CAD) is the use of software to create or optimize designs of fabrics, patterns, and garments. This technology allows designers to visualize and experiment with colours, textures, and patterns digitally before physical production, reducing the need for physical prototypes. |
| **Digital Twin (DT)** | A digital twin is a 3D virtual reality copy of a physical product, containing all the available information of the product. Besides design-related information, also real-time, dynamic data such as maintenance information, etc. can be attached and made available through a portal. By making all this information accessible, decision making about the product is much easier (Rantala et al., 2023; Ahmad et al., 2020). |
| **Digital product passport (DPP)** | Digital Product Passports (DPP) are digital profiles attached to products, providing detailed information about their origin, materials, usage and end-of-life handling. DPPs offer complete transparency about a product's lifecycle and ensure authenticity. By including information about environmental impacts, DPPs can support sustainable industry practices and inform consumer choices. |
| **Internet-of-Things (IoT)** | The IoT refers to a system of interconnected sensors, instruments and other devices, creating an information network for the collection exchange and analysis of large amounts of real-time data. This technology turns stand-alone objects into smart and connected objects. In manufacturing, IoT can be used to operate, optimise and monitor production machines, to facilitate supply chain integration and to track products throughout their productions process, delivering improvements in productivity and efficiency, as well as cost reductions (Rantala et al., 2023). |
| **Machine Learning (ML)** | Machine learning (ML) is a basic version of AI that enables robots and machines to detect working conditions automatically (Ahmad et al., 2020). |
| **Machine vision** | Machine vision is the technology and methods used to provide imaging-based automatic inspection, analysis, and interpretation. In textiles, machine vision is used to automate the detection of defects during the manufacturing process, |

| | |
|---|---|
| | or to automate colour or fibre identification during sorting. It relies on cameras, sensors, and algorithms to analyse textile materials in real-time. |
| **Metaverse** | We have a 3D model of the whole world, updated in real time. People can be there as avatars. All people can wear goggles, which can switch from AR to VR to real-world modes. In the real-world mode, people see the world like we do now. In the AR mode, the user can view all digital information on top of the real world. In the VR mode, the user can "teleport" to any location in the world (and meet one's friends as avatars) or travel in time (Rantala et al., 2023). |
| **NFT** | Non-fungible tokens (NFTs) are digital (blockchain based) assets representing ownership or proof of authenticity of a specific item or piece of content. Fashion NFTs can be virtual garments worn in virtual worlds.  (Boston Consulting Group, 2022) |
| **Platform** | Digital platforms are intermediaries between supply and demand and can be used to facilitate the sale of second-hand items between consumers, between companies and consumers or between companies, or coordinate clothing repair between consumers or brands and a network of tailors. |
| **RFID** | Radio-Frequency Identification (RFID) is one of the main sensors used to collect large datasets of real-time data using wireless technologies and allows connecting objects in the Internet of Things. It is widely utilised for supply chain management, production management, warehouse management and customer relationship management. RFID makes it possible to track and monitor products throughout production and logistics and it avoids inaccurate entries, mislabelling and misplaced stocks (Ahmad et al., 2020). |
| **Robotics** | Robots can work alongside humans in complex working environments. Robot technology allows automation of production and management processes, resulting in cost reduction. Many large brands use robots in their warehouses for inventory management (Ahmad et al., 2020). |
| **Sensors** | A sensor is a device that detects and responds to physical inputs such as light, heat, motion, pressure, or other environmental changes, converting these into signals that can be measured or monitored. For example, sensors can detect fabric defects, ensure proper alignment in weaving, or identify product types, colours or fibre composition during automated sorting. |
| **Virtual reality (VR)** | Virtual Reality (VR) is a computer-generated simulation that immerses users in a fully interactive, 3D environment, often experienced through specialized headsets. In textiles, VR can be applied to simulate fabric designs, patterns, and textures, allowing designers to visualize and experiment with fabric or garment designs in a virtual space, without physically producing the textiles. |
| **Wearables** | IoT sensors can also be attached or built into clothes. These so-called 'wearable electronics' can monitor the wearer's vital signs, such as blood pressure, body temperature or activity level, or location, using GPS tracking, and are emerging in the field of healthcare, sports and safety. |

## Annex 4: List of interviewees

Semi-structured interviews with 19 European fashion companies and SMEs, as well as sector organisations and expertise centres on sustainable fashion, were conducted in the frame of this study.

| No. | Value chain position | Organisation type | Organisation description |
|---|---|---|---|
| **1** | Product design | Industry - SME | Digital fabric library |
| **2** | Product design | Textiles expert | Fashion academy |
| **3** | Textile manufacturing | Industry - SME | Production |
| **4** | Textile manufacturing | Industry - SME | Production |
| **5** | Textile manufacturing | Industry - large company | Production and retail |
| **7** | Retail and customer interactions | Industry - SME | Retail |
| **8** | Product use and lifecycle management | Industry - SME | Online rental platform |
| **9** | Reverse flows | Digital solution provider | Facilitation of take-back systems |
| **10** | Reverse flows | Digital solution provider | Sorting for recycling, micro particle tracing technology |
| **11** | Value chain management, collaboration and transparency | Topic expert | DPP expert |
| **12** | Value chain management, collaboration and transparency | Digital solution provider | DPP solutions provider |
| **13** | Other | Sector organisation | Design and fashion support centre |
| **14** | Other | Digital solution provider | Digitalisation expert |
| **15** | Other | Sector organisation | Cluster organisation for fashion/textiles |
| **16** | Other | Topic expert | Digitalisation expert |
| **17** | Product use and lifecycle management | Industry - SME | Online repair platform |
| **18** | Product use and lifecycle management | Industry – SME | Online repair platform |
| **19** | Product use and lifecycle management | Industry – SME | Tailors |

European Topic Centre on
Circular economy and resource use
https://www.eionet.europa.eu/etcs/etc-ce

The European Topic Centre on Circular economy and resource use (ETC CE) is a consortium of European institutes under contract of the European Environment Agency.

European Environment Agency
European Topic Centre
Circular economy and resource use