What is behind the producer GHG emissions footprint of textile and clothing in the EU-27? An environmentally extended multi-regional input-output analysis

Luis Yamuza-Blanco [a,*], Fabio Monsalve [b], Rocío Román-Collado [a,c], María Teresa Sanz-Díaz [a]

[a] *Universidad de Sevilla, Calle San Fernando 4, 41004 Sevilla, Spain*
[b] *Universidad de Castilla–La Mancha, Av. de España s/n, 02001, Albacete, Spain*
[c] *Universidad Autónoma de Chile, Av. Pedro de Valdivia 425, 7500912 Providencia, Chile*

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A B S T R A C T

The textile and clothing industry is globally recognized as the fourth highest contributor to environmental pressure, requiring substantial volumes of raw materials and resources from various sectors. Moreover, it contributes approximately 4 % of global greenhouse gas emissions annually. The final producers in this industry bear a portion of the responsibility and have the ability to directly address and mitigate the sustainability issues and environmental impacts that occur throughout their supply chains. Against this background, the article aims to analyse the greenhouse gas emissions footprint of the European Union-27's final textile and clothing producers from 1995 to 2022. The methodology applied combines an Environmentally Extended Multi-Regional Input-Output analysis with a producer footprint analysis, utilizing the Exiobase database. These methods enable the tracking of emissions both directly and indirectly generated throughout the production chain of final goods, and the allocation of these emissions to the country of residence of the final producer. The results indicate that the emissions footprint of producers in the European Union-27's textile and clothing industry decreased by approximately 50 % during the period. However, while the domestic producer footprint saw a reduction of 61 %, the imported emissions decreased by only 27 %. This discrepancy highlights various inefficiencies, demonstrating that importing has a greater emissions impact than domestic production. Additionally, a decoupling analysis is conducted to examine the degree of disassociation between greenhouse gas emissions and the intermediate inputs used throughout the European Union-27's textile and clothing supply chain. In this respect, some supplier partners have positively contributed to decarbonization, underscoring the need for strategic trade relations.

1. Introduction

The textile and clothing (T&C) industry is globally recognized as the fourth highest contributor to environmental pressure (Amicarelli et al., 2022; EEA (European Environment Agency), 2023) and a significant source of greenhouse gas (GHG) emissions (Diddi et al., 2019; Hole and Hole, 2019; Saha et al., 2021; United Nations, 2023), annually contributing approximately 4 % of global emissions (EMF (Ellen Macarthur Foundation), 2021). These GHG emissions have a detrimental impact on the environment, being the main driver of climate change (Peters et al., 2015; Nimkar, 2018), which results in rising average temperatures and more extreme climate events (EP (European Parliament), 2023a).

The generation of GHG emissions in the T&C industry predominantly occurs during the energy-intensive phases, such as the manufacturing of natural fibres (Beton et al., 2014; EMF (Ellen Macarthur Foundation), 2017) and synthetic fibres (Claudio, 2007; EMF (Ellen Macarthur Foundation), 2017), the manufacturing process (Huang et al., 2017), and distribution activities (Beton et al., 2014). While the industry is energy intensive by nature (Palamutcu, 2010), the heavy reliance on fossil-based energy in developing countries (Ozturk, 2005; Liang et al., 2023), coupled with inefficient energy use (Haseeb et al., 2020), exacerbates the environmental pressures and GHG emissions of the industry in these regions. Notably, T&C products manufactured in China have a carbon footprint 40 % larger than those produced in the EU (Imran et al., 2023).

The production process in the T&C industry requires substantial volumes of raw materials and resources from other sectors. This demand for intermediate inputs results in environmental impacts along the T&C supply chains, including the generation of GHG emissions, which appear to be overlooked by the final producers or manufacturers that create finished products ready for the end consumers. However, these producers bear a portion of the responsibility for mitigating said environmental impacts and have the ability to directly address the sustainability issues that occur throughout their supply chains (Wiebe, 2018). There is thus a need to account for both the direct GHG emissions of the T&C industry and the indirect emissions induced by the demand for intermediate inputs.

The T&C supply chains are long, complex and dynamic (Kozlowski et al., 2016), involving numerous phases from raw material manufacture to disposal activities (Shen and Smith, 2015; Kozlowski et al., 2016; Amutha, 2017), with several actors participating at different levels (Hrouga and Michel, 2023). This makes it a challenge to manage traceability and transparency (Giri and Shankar Rai, 2013; Malik et al., 2021), while the ability to rapidly update environmental standards, regulations and policies is crucial (Zor, 2023).

The T&C industry in developed countries is characterized by outsourcing and significant imports (Dunford, 2004; Girneata and Dobrin, 2015). Production is primarily located in developing countries (Pal and Gander, 2018; de Oliveira Neto et al., 2020), driven by the labour-intensive nature of the industry and the pursuit of lower wage costs (Olsen et al., 2004; Keenan et al., 2004; Kumar et al., 2022). The European Union (EU) has followed this outsourcing trend (Stengg, 2001; EURATEX, 2020; Valodka et al., 2020; EURATEX, 2022), with imports of T&C products amounting to 177 billion euros in 2022, compared to exports of 103 billion euros (Eurostat, 2024). The main supplier partners of the 27 EU Member States (EU-27) are China (34.79 %), Bangladesh (13.10 %), Turkey (9.97 %), India (5.89 %) and Indonesia (2.25 %).

The EU is committed to addressing the environmental impacts of the T&C industry and enhancing its sustainability, as reflected in the European Green Deal, the Circular Economy Action Plan, and the European Industrial Strategy (EC (European Commission), 2024a, 2024b, 2024c). One key area of improvement is air pollution and GHG emissions, with the EU targeting levels that are not harmful to health and natural ecosystems (EC (European Commission), 2024d). In the same vein, the EU aims to lessen the environmental impact of T&C supply chains (EP (European Parliament), 2023b, 2023c) and extend the life cycle of T&C products (EC (European Commission), 2024e), regardless of where production occurs (EC (European Commission), 2024f), thereby making production more sustainable and environmentally friendly (EC (European Commission), 2024g).

To achieve the EU's objectives for this industry, a detailed understanding is needed of how the responsibility for emissions is distributed among different actors along the EU-27's T&C supply chain. According to scientific literature, there are two primary approaches to study this issue: Life Cycle Assessment (LCA) and Multi-Regional Input-Output (MRIO) modelling, which includes Consumption Based Analysis (CBA) and Producer Footprint (PF). LCA assesses the environmental impact of specific products from cradle to grave (Wiedmann and Minx, 2008). Most previous studies on emissions footprint applications in the T&C industry use LCA methodology (Manda et al., 2015; Serweta et al., 2019; Payet, 2021; Zhao et al., 2021; Stridsland et al., 2023). CBA accounts for the emissions generated directly and indirectly in the production processes of final goods demanded by a country (Minx et al., 2009). Although CBA has been less widely used in the T&C industry, there are notable applications within the EU context. For instance, Bonilla et al. (2015) assess the consumption footprint of the T&C value chain, identifying strategies to minimize it; Peters et al. (2021) calculate environmental and social indicators to assess the impacts of the global clothing and footwear value chain; Mair et al. (2016) examine the sustainability implications of meeting Western European demand for T&C products; and Valodka and Snieska (2020) and Valodka et al. (2020) study the consumption footprint of clothing products from China, India and Turkey. Additionally, Malik et al. (2021) investigate the negative social spillover effects of textile production to satisfy EU consumption. Lastly, PF tracks emissions generated directly and indirectly along the production chain of final goods and allocates them to the final producer's country of residence, regardless of where these goods are exported or consumed (López et al., 2019; Ortiz et al., 2020a; Ortiz et al., 2020b). Also known as "sales-based inventory" or "final-product-based emissions accounting" (Kanemoto et al., 2012; Wiebe, 2018), it is based on the producer's global responsibility (López et al., 2019) and can be used to determine where the emissions hotspots occur along the global production chain (Wiebe, 2018). To our knowledge, there are no studies to date that analyse the PF of the T&C industry, in any region.

Given the EU's vision for improving this industry, it is pertinent to analyse the supply chains of the EU-27's final producers and identify the GHG emissions hotspots, in order to propose actionable measures. The EU has regulatory control over manufacturers within its territory and can implement actions to reduce GHG emissions from their production processes. This article aims to analyse the GHG emissions footprint of the EU-27's final T&C producers and its evolution from 1995 to 2022, considering all emissions generated across the supply chain. This wide-ranging analysis of the EU-27's T&C industry can provide a detailed understanding of the emissions structure of the final producers and the specific measures they should take to improve their production chains.

The novelty of this paper is that it calculates the PF for the T&C industry -to our knowledge, the first such application in the literature- and it carries out a long-term analysis of the EU-27 as a whole, involving the deflation of a comprehensive MRIO database with the most available information. In addition, this paper presents a novel application of a decoupling analysis to study the level of disassociation between GHG emissions generation calculated with the PF approach and intermediate inputs utilized throughout the supply chain of the EU-27's final T&C producers.

After this introduction, the structure of the paper is as follows. The next section describes the methodology and database utilized. The results and discussion section examines the outcomes of the research and compares them with those obtained by previous studies. Finally, the conclusions section summarizes the findings of the analysis.

2. Methods and data

2.1. Environmentally extended multi-regional input-output model and the producer footprint

The methodology used in this paper is the Environmentally Extended Multi-Regional Input-Output (EEMRIO) model, as it enables an analysis of the multilateral trade transactions between industries of different countries (Andrew et al., 2009; Miller and Blair, 2009; Wiedmann, 2009; Gao et al., 2020).

The EEMRIO, which is a combination of input-output tables with consistent environmental data (Minx et al., 2009), has countless applications (Suh, 2009; Hoekstra, 2010) and can be used to assess the environmental impacts of countries, industrial sectors, product groups or companies (Wiedmann and Minx, 2008). It yields integral and solid estimates (Miller and Blair, 2009), minimizes the chance of double counting (Pandey et al., 2011), and is not labour- or data-intensive (Wiedmann, 2009).

The initial equation of the MRIO model can be expressed in matrix terms as follows (Miller and Blair, 2009):

$$X = AX + Y \tag{1}$$

where X is a vector that represents the total output of each sector, A is a matrix of technical coefficients which shows the intermediate inputs that each sector needs to produce one unit of its products and Y is a vector of final demand.

Isolating X from eq. (1), the basic equation of the Leontief model can be obtained:

$$X = (I - A)^{-1} \bullet Y = L \bullet Y \tag{2}$$

For estimating emissions, the environmental extension of eq. (2) is used, which indicates the emissions generated by final demand (Miller and Blair, 2009; Bhar et al., 2024):

$$E = \hat{e} \bullet (I - A)^{-1} \bullet Y = \hat{e} \bullet L \bullet Y \tag{3}$$

where $\hat{e}$ is the emission coefficient which is obtained by dividing the emissions by the output and indicates the amount of emissions that are directly and indirectly released to produce one unit of production. Multiplying this emission coefficient by $L = (I - A)^{-1}$ gives the emissions multiplier. Y is the matrix of final demand. Consequently, E is a matrix that represents all the direct and indirect emissions generated to satisfy the total final demand.

The PF is calculated by modifying the final demand matrix in eq. (3); specifically, the Y matrix is summed horizontally and placed on the main diagonal ($\hat{Y}$). The diagonalized matrix $\hat{Y}$ computes the total final demand without distinction between domestic and foreign final demand or between the countries that ultimately consume the final production (Ortiz et al., 2020a; Ortiz et al., 2020b).

$$\overline{E} = \hat{e} \bullet (I - A)^{-1} \bullet \hat{Y} = \hat{e} \bullet L \bullet \hat{Y} \tag{4}$$

The PF can be estimated by summing the columns of the matrix $\overline{E}$ as follows:

$$PF^{s} = \sum_{r,i,j} \overline{E}_{ij}^{rs} \tag{5}$$

The superscript on the left corresponds to the exporting region and the superscript on the right refers to the importing region. Therefore, multilateral exports and imports of intermediate and final goods are included. The subscript on the left corresponds to sector i of region r and the subscript on the right corresponds to sector j of region s. In this case, sector j is the EU-27's T&C industry.

As in Román-Collado et al. (2021), eq. (5) can be disaggregated as follows:

$$PF^{s} = ENI^{s} + EfONI^{s} + EI^{s} \tag{6}$$

The Emissions of National Industry (ENI) are those emissions embodied in the final goods of the reference sector of a specific country (s) that are produced by the same reference sector, therefore r = s and i = j:

$$ENI_{j}^{s} = \overline{E}_{ij}^{rs} \tag{7}$$

The Emissions from Other National Industries (EfONI) are those emissions embodied in the final goods of the reference sector of a specific country (s) that are produced by other industries of the same country, therefore r = s and i ≠ (j)

$$EfONI_{j}^{s} = \sum_{i=1}^{n} \overline{E}_{ij}^{rs} \tag{8}$$

The Emissions Imported (EI) are those emissions embodied in the final goods of the reference sector of a specific country that are produced by other countries, therefore r ≠ (s)

$$EI_{j}^{s} = \sum_{r=1}^{m} \left(\sum_{i=1}^{n} \overline{E}_{ij}^{rs} \right) \tag{9}$$

Based on these components, the Domestic Producer Footprint (DPF) can be defined as the sum of emissions generated by national industries:

$$DPF^{s} = ENI^{s} + EfONI^{s} \tag{10}$$

2.2. Decoupling analysis

The term "decoupling" was first introduced by the OECD in 2002 to refer to breaking the link between economic growth and energy consumption (Wang et al., 2019). There are two main types of decoupling, relative and absolute, depending on whether whatever is being measured varies relative to economic growth (UNEP (United Nations Environmental Program), 2011; Wu et al., 2023). Tapio (2005) later improved the decoupling theory with the introduction of a decoupling index, which opened up the concept to a wider variety of applications (Wang and Su, 2020). Tapio's index is generally considered superior to other approaches because it exhibits consistent decoupling trends, is not constrained by the duration of the period, and allows for a wide range of decoupling states (Wu et al., 2018).

Tapio's (2005) decoupling index is used to evaluate whether an environmental impact can be decoupled from economic growth. This index is based on the concept of elasticity, where environmental elasticity is defined as the percentage change in an environmental impact resulting from a 1 % change in the chosen economic driving force. Following previous applications (Sanyé-Mengual et al., 2019; Wang and Su, 2020; Ozturk et al., 2021; Zhang and Han, 2022; Liang et al., 2023; Baajike et al., 2024), the current paper proposes a novel application of this decoupling index, where the environmental impact under examination is GHG emissions and the economic indicator is the intermediate inputs involved in the economic activity of the producers' supply chain. These intermediate inputs are selected as the economic indicator for the decoupling index due to their significant role in the outsourcing process of the EU-27's T&C industry in recent decades. Calculating the sensitivity of emissions to changes in inputs from supplier partners will enable the identification of the most efficient suppliers in terms of GHG emissions produced. This information can contribute to the decarbonization of the EU-27's T&C industry value chain.

The calculation of the decoupling index for the period 1995–2022 involves several steps. The first step is to calculate the year-on-year change in the GHG emissions of the EU-27's T&C industry ($\%GHG_{T}^{s}$) and of the inputs ($\%Inputs_{T}^{s}$), both attributed to the supplier partner (s). These variables are computed using the PF approach and are measured in monetary units (constant 2008 prices). Second, the geometric average of these two variables is calculated for the entire period, denoted as ${T_{GHG}}^{s}$ and ${T_{Inputs}}^{s}$, respectively. Finally, the decoupling index (DI^{s}) is calculated as follows:

$$DI^{s} = \frac{{T_{GHG}}^{s}}{{T_{Inputs}}^{s}} = \frac{\sqrt[n]{\prod_{T=1}^{n} \%GHG_{T}^{s}}}{\sqrt[n]{\prod_{T=1}^{n} \%Inputs_{T}^{s}}} \tag{11}$$

Following García-Alaminos et al. (2020) and Wang et al. (2024), the decoupling states can be classified as follows:

		DI^{s}	${T_{GHG}}^{s}$	${T_{Inputs}}^{s}$
Decoupling	Strong	< 0	< 0	> 0
	Weak	0–0.8	> 0	> 0
	Recessive	> 1.2	< 0	< 0
Negative decoupling	Strong	< 0	> 0	< 0
	Weak	0–0.8	< 0	< 0
	Recessive	> 1.2	> 0	> 0
Coupling		0.8–1.2	$\in \mathbb{R}$	$\in \mathbb{R}$

The decoupling states can be described as follows. There are three desirable states of decoupling, insofar as they either contribute to reducing the environmental impact or increasing it at a lower rate than the growth in the economic indicator. Strong decoupling ($DI^s < 0$) implies that GHG emissions fall over the analysed period, while the inputs increase. Weak decoupling ($0 < DI^s < 0.8$) happens when both GHG emissions and inputs increase, but the percentage change in GHG emissions is smaller than the corresponding change in inputs. Recessive decoupling ($DI^s > 1.2$) happens when GHG emissions and inputs both fall, and the percentage change in GHG emissions is greater than the corresponding change in inputs. There are three non-desirable states of decoupling, insofar as they either contribute to increasing the environmental impact or reduce it at a lower rate than the decrease registered by the economic indicator. Strong negative decoupling ($DI^s < 0$) occurs when GHG emissions increase over the analysed period, whereas the inputs fall. Weak negative decoupling ($0 < DI^s < 0.8$) happens when both GHG emissions and inputs fall, but the percentage change in inputs is greater than the corresponding change in GHG emissions. Recessive negative decoupling ($DI^s > 1.2$) occurs when both GHG emissions and inputs increase, but the percentage change in GHG emissions is greater than the corresponding change in inputs. Decoupling index values between 0.8 and 1.2 indicate complete coupling between the percentage change in GHG emissions and in inputs.

2.3. Database

This paper relies on the Exiobase 3.9.4 database (Stadler et al., 2018), which provides a time series of MRIO tables for 49 regions and 163 industries, as well as a variety of satellite datasets (Tukker and Dietzenbacher, 2013). The data selected are annual and cover the period from 1995 to 2022.

Exiobase has been chosen because it provides detailed coverage of 84.04 % of the imports from the supplier partners of the EU-27's T&C industry, its robustness is supported by literature (Stadler et al., 2018), and it covers a long time period. Regarding the units used, the GHG emissions are expressed in millions of kilograms and the production data are expressed in millions of euros.

The T&C industry analysed comprises manufacture of textiles (47), manufacture of wearing apparel, dressing and dyeing of fur (48) and tanning and dressing of leather, manufacture of luggage, handbags, saddlery, harness and footwear (49). According to the European Classification of Economic Activities (NACE-2) (Eurostat, 2008) and Exiobase data concordances (EXIOBASE, 2023), this research covers the whole T&C industry, which ensures the quality of the analysis and results. The analysis focuses on the current EU-27, regardless of the countries that joined or left the EU during the studied period.

The MRIO tables from Exiobase have been deflated to 2008 constant prices to remove the effect of price changes. Following the example of Duarte and Serrano (2021), Yuan et al. (2022a) and Yuan et al. (2022b), and due to the data limitations of Exiobase, the deflation process combines sectorial World Input-Output Database (WIOD) deflators for desegregated categories from 1995 to 2014 (Timmer et al., 2015) and country GDP deflators from the World Bank and OECD National Accounts from 2015 to 2022 (World Bank, 2024) (Appendix A).

The calculation of the GHG emissions data has been done in two steps. First, satellite datasets of Exiobase have been added for CO_2, CH_4 and N_2O components. Second, the following calculation has been applied (IPCC (Intergovernmental Panel on Climate Change), 2014): $GHG = 1 \bullet CO_2 + 28 \bullet CH_4 + 265 \bullet N_2O$.

3. Results and discussion

Calculating the PF allows the tracking of the GHG emissions directly and indirectly generated along the production chain of final goods, and their allocation to the final producer's country of residence. The present analysis is focused on the production chain of the EU-27's final T&C producers during the period from 1995 to 2022.

During this period, the PF of the EU-27's T&C industry decreased by approximately 50 %, as shown in Fig. 1. A closer examination reveals three distinct subperiods. In the first subperiod, from 1995 to 2008, GHG emissions decreased by 42 %, although there was an increase following the removal of world trade quotas on T&C products in 2002 (Islam et al., 2016; Valodka et al., 2020; Hong et al., 2024). In the second subperiod, from 2008 to 2020, GHG emissions decreased by 53 %, with the significant reduction in the early years triggered by the 2008 financial crisis (Curran and Zignago, 2010). Finally, in the third subperiod, from 2020 to 2022, GHG emissions increased by 83 %, despite a decrease around the time of the COVID-19 crisis (Blancheton, 2021; Zhao and Kim, 2021; Leal Filho et al., 2022).

After this overview, the results and discussion are divided into three subsections. The first and second subsections present a detailed analysis of the DPF and the EI, respectively. The third subsection presents the results of the EU-27's T&C supply chain decoupling analysis.

3.1. Domestic producer footprint of the EU-27's T&C industry

The DPF of the EU-27's T&C industry shows a reduction of approximately 61 % in GHG emissions during the period analysed. It therefore accounts for a smaller proportion of the PF, dropping from 68 % in 1995 to 53 % in 2022, in constant terms.

The DPF can be divided into ENI (emissions from the EU-27's T&C industry) and EfONI (emissions from other industries in the EU-27), as shown in eqs. (7, 9, 10). Both components of the DPF have become cleaner in terms of GHG emissions; however, the intermediate inputs used by the EU-27's T&C industry have been more polluting in terms of GHG emissions than the industry's own activity. Starting with ENI, as shown in Fig. 2, these emissions have been reduced by 68 % during the period analysed, and therefore carry less weight in explaining the DPF, dropping from a share of 9 % in 1995 to 6 % in 2022, in constant terms. The reduction of GHG emissions in the EU-27's T&C industry is related to improvements in efficiency (EC (European Commission), 2015; EC (European Commission), 2017a, 2017b; EC (European Commission), 2019; EC (European Commission), 2020), the optimization of energy consumption (EC (European Commission), 2003; EPC (European Parliament and Council), 2008; Directive 2010/75/EU of the European Parliament and of the Council, 2010; Directive 2012/27/EU of the European Parliament and of the Council, 2012), and the outsourcing strategies that have shifted emissions abroad (Taplin, 2006; Girneata and Dobrin, 2015; Valodka et al., 2020). The EU-27 has the least emission-intensive T&C industry of all the regions studied and, during the analysed period, has managed to reduce the generation of ENI per unit of production by 66 %, in constant terms (Table 1).

Turning to EfONI, these emissions have been reduced by 60 % during the analysed period. Among the main sources of these emissions, as shown in Fig. 2, the fossil fuel power generation stands out, representing 33 % of EfONI in 2022. However, this industry decreased its generation of GHG emissions by 58 % during the period analysed, in constant terms. The reduction of emissions by domestic energy supplies is reflected in improvements in the carbon intensity of the European phases of the chain (Scarlat et al., 2022), and has acted as an inhibitor of emissions generated in the supply chain of the EU-27's final T&C producers. In fact, during the period studied, the use of renewable energies increased while the share of fossil fuels in the energy mix of the EU-27's T&C industry decreased (Tutak and Brodny, 2022; Román-Collado et al., 2023). Furthermore, all the other industries reduced their GHG emissions during the analysed period, highlighting the significant improvements in the European phases of the EU-27's T&C value chain.

The emissions reduction of 88 % in the EU-27's chemical industry seems to be due to investments in energy efficiency and the implementation of N_2O abatement technologies (Bauer et al., 2023). Analyses

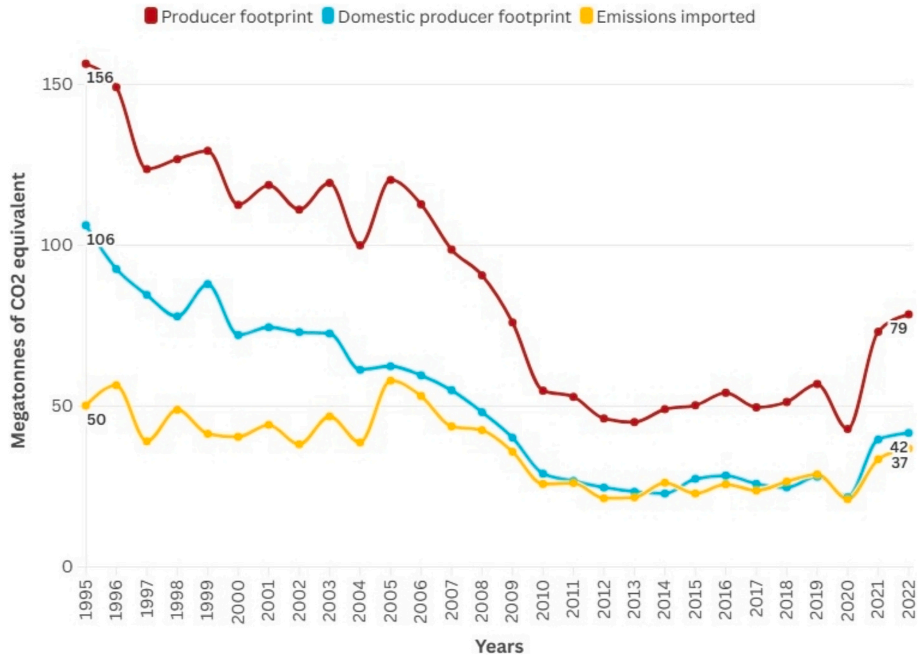

Fig. 1. Evolution of the producer footprint, domestic producer footprint, and emissions imported by the EU-27's T&C industry during the period 1995–2022.

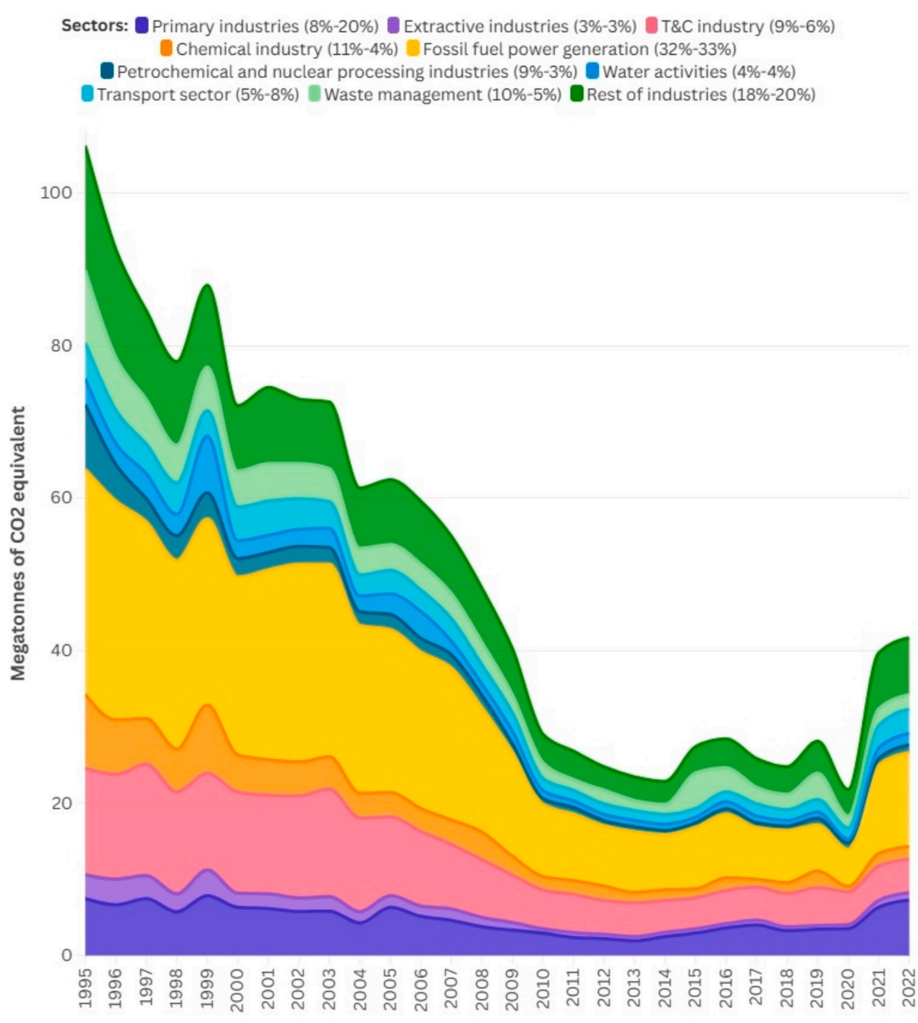

Fig. 2. Domestic producer footprint of the EU-27's T&C industry, detailed by industry, during the period 1995–2022.

of GHG emissions indicate that the N_2O component has the greatest impact (IPCC (Intergovernmental Panel on Climate Change), 2014), with the observed improvement in emissions demonstrating the efficiency of N_2O abatement approaches. Additionally, the EU-27's agricultural sector effectively reduced its emissions during the period analysed (Mohammed et al., 2020; Harsányi et al., 2021; Peng et al., 2024), mainly through the introduction of better production techniques and the improvement of energy use (Wicki and Wicka, 2022).

3.2. Emissions imported by the EU-27's T&C industry

As shown in Fig. 1, the EI of the EU-27's T&C industry have been reduced by 27 % during the period analysed. They account for a larger share of the PF, moving from 32 % in 1995 to 47 % in 2022, in constant terms. During this period, many European manufacturing activities were offshored and outsourced to developing countries (Schwörer, 2013; Mohiuddin et al., 2019). The EU-27's T&C industry followed this trend, with the production of GHG emissions also shifting to outside the EU (Wong and Au, 2007; Valodka et al., 2020), in an effort to reduce production costs (Adler, 2004; Martínez-Mora and Merino, 2021) and access laxer environmental policies (Assogbavi and Dées, 2023; Eskander and Fankhauser, 2023). Apart from the environmental impact, the offshoring and outsourcing of T&C production in developing countries have led to poor working conditions (Barrientos et al., 2016), negative impacts on human health (Al-Tohamy et al., 2022), and workplace accidents (Malik et al., 2021).

As shown in Fig. 3, the EI can be broken down by supplier partner of the EU-27's T&C industry. In this context, the United States, RoW Africa, and RoW Asia and Pacific were the most polluting supplier partners in terms of GHG emissions in 1995. By 2022, China, RoW Asia and Pacific, and Turkey had become the most polluting suppliers. During the analysed period, China, India, and Indonesia experienced the most significant growth in GHG emissions, increasing by 504 %, 1103 %, and 396 %, respectively.

The results obtained are in line with previous scientific literature: Mair et al. (2016) indicate that China, India and Indonesia are responsible for a growing share of the emissions of Western Europe's T&C industry; Valodka et al. (2020) report that China, India and Turkey are the main supplier partners of EU's T&C industry and have been generating increasing emissions; and Bonilla et al. (2015) point out that China and Turkey are important regions for the offshoring of certain phases of the EU-27's T&C supply chain.

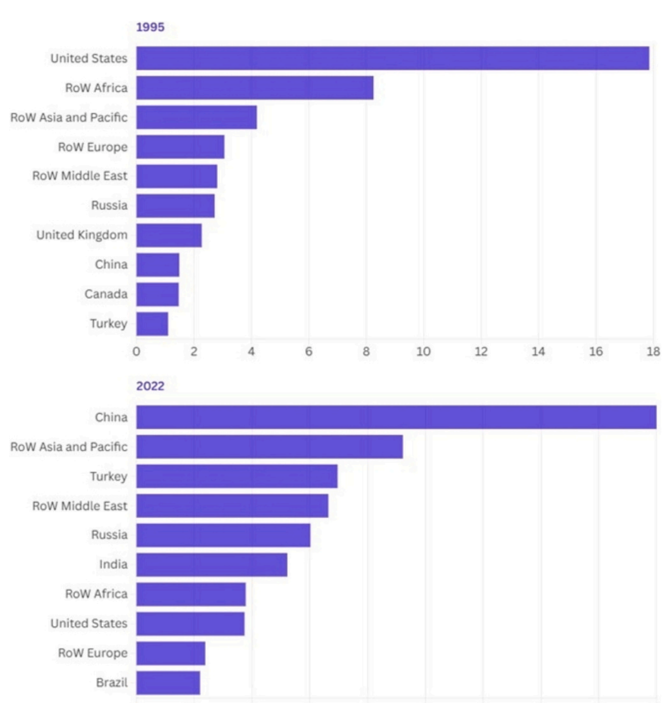

Fig. 3. Emissions imported by the EU-27's T&C industry, detailed by the top ten supplier partners for the years 1995 and 2022.

The EI can be detailed by industry, as shown in Fig. 4. The supply chain of the EU-27's final T&C producers is particularly dependent on the primary industries of China, India and Indonesia (Mair et al., 2016), and the energy sectors of Russia and China (Table B1, Appendix B). Although the efficiency of the supplier partners' energy sectors improved during the period analysed, they produced more GHG emissions per unit of production than the EU-27 did in 2022, and are therefore a source of inefficiency. In fact, the energy generation of developing countries is more GHG-intensive as the energy mix depends more on fossil fuel resources (Ozturk, 2005; Azad and Chakraborty, 2023; Liang et al., 2023) and energy use is more inefficient (Haseeb et al., 2020).

The T&C industries of China, India, and Indonesia were the most polluting in 1995, accounting for 85 % of GHG emissions in the EU-27's T&C value chain. By 2022, Turkey and Indonesia had become the most polluting, representing 78 % of emissions. The T&C industries of Turkey and Indonesia increased their shares of GHG emissions in the EU-27's T&C value chain by 4140 % and 30 %, respectively. Meanwhile, the rest of the supplier partners demonstrated improvements over the analysed period, as shown in Table 1, although they remain significantly more polluting than the EU-27's T&C industry. These results are in line with previous studies of China, India, Turkey and Indonesia (Mair et al., 2016; Valodka et al., 2020).

The development of outsourcing strategies is closely linked to an increase in transport activities (McCarthy and Anagnostou, 2004; Wei et al., 2024), and therefore in GHG emissions. Despite significant changes in the transport options between European countries and Asia (Alpkokin et al., 2016), sea transport remained the main option during the period analysed due to its low cost (Jiang et al., 2020). In fact, China's GHG emissions from shipping grew from 2.60 million tons CO2 equivalent in 1980 to 39.95 million tons in 2015, and are expected to continue increasing (To and Lee, 2018). Emerging alternatives for transport between these regions can help reduce GHG emissions, such as the China-Europe Freight Train (CEFT) (Chen, 2023) or the New International Land-Sea Trade Corridor (ILSTC) (Huang et al., 2023).

The increase in the EI of the EU-27's T&C industry, coming especially from developing countries, seems to be correlated with the EU's continuing openness to imports and reimports of T&C products after preparation or transformation in third countries during the analysed period (EC (European Commission), 1995a, 1995b; EC (European Commission), 1996a, 1996b, 1996c, 1996d). In accordance with the EU's objectives for GHG emissions, companies and governments should seek to ensure the sustainability of T&C production by investing in low carbon energy infrastructures (Mair et al., 2016) and should rethink their strategy to reduce the EI, since they are the largest source of polluting emissions.

Finally, it is important to point out that the dependence on external suppliers (Hobson, 2016) and the management of the supply chains is among the main challenges for the development of a circular economy in the T&C industry (Hrouga and Michel, 2023). The EU should therefore take this into account when developing policies and implementing related measures.

3.3. Decoupling analysis of the supply chain of the EU-27's final T&C producers

The decoupling index (see eq. 11) illustrates the sensitivity of GHG emissions to changes in intermediate inputs from supplier partners during the period from 1995 to 2022. This index can be used to identify the most efficient supplier partner in terms of GHG emissions produced, thereby contributing to the decarbonization of the EU-27's T&C industry

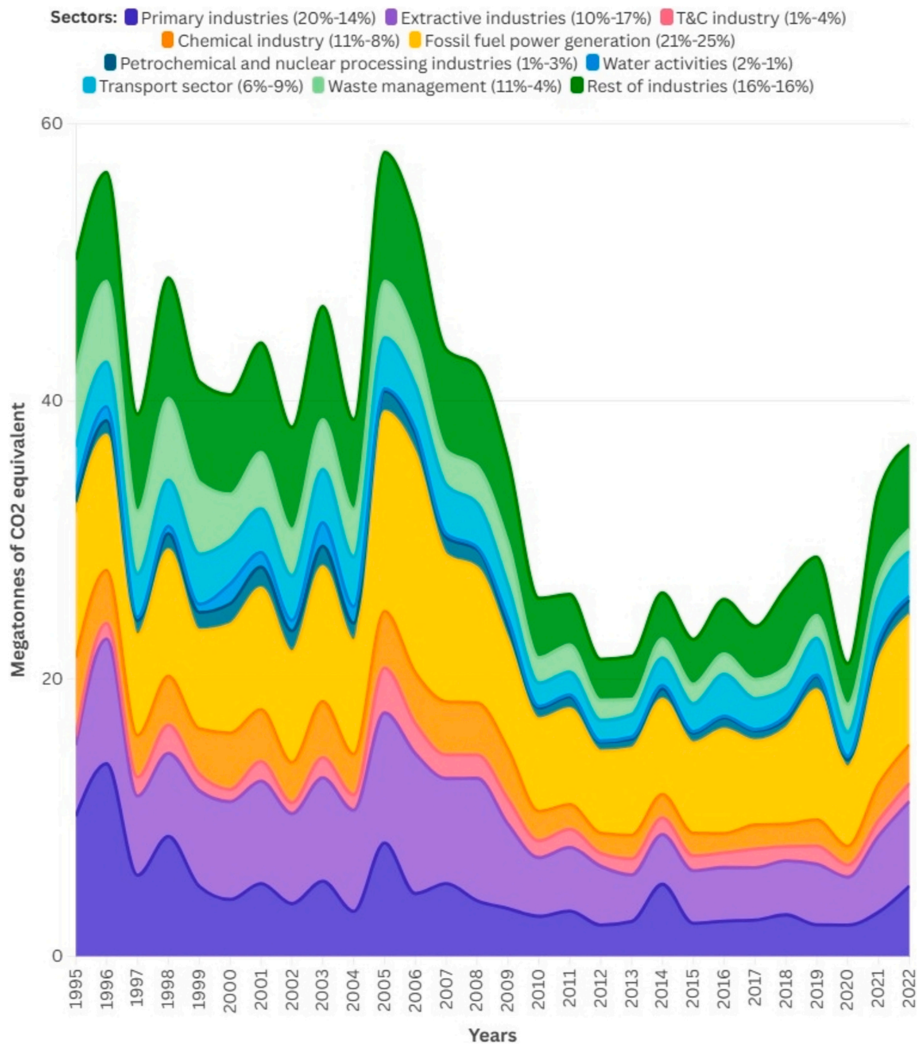

Fig. 4. Emissions imported by the EU-27's T&C industry, detailed by industry, during the period 1995–2022.

value chain. As shown in Fig. 5, the EU-27's T&C supply chain exhibits varying results for the decoupling index. The graph shows only the supplier partners that account for more than 7 % of EI in 2022.

The EU-27 successfully decoupled GHG emissions from intermediate inputs, showing results close to strong decoupling throughout the period. Specifically, the intermediate inputs required in the EU-27's T&C supply chain decreased by 9 %, while GHG emissions decreased by 59 %. As a result, the European segments of the supply chain experienced a reduction in emissions during the analysed period. This decrease in emissions appears to be linked to advancements in energy efficiency (Trotta, 2019; Nepal et al., 2021), electricity generation (Rodrigues et al., 2020), and production techniques (Brunel, 2014).

Regarding the supplier partners, a wide variety of decoupling states are found. The supplier countries that performed best in terms of decoupling GHG emissions from intermediate inputs during the analysed period were Switzerland, South Korea, RoW Europe, Australia, the United Kingdom, Canada, and the United States. Although these supplier partners are less significant in terms of emissions, only accounting for 13 % of the EI in 2022, they represent 33 % of the intermediate inputs required in the EU-27's T&C supply chain. These supplier partners are located in the three desirable states of the decoupling index (strong decoupling, weak decoupling, and recessive decoupling). As such, they either contribute to the decarbonization of the EU-27's T&C industry value chain by reducing the PF of the EU-27's T&C industry, or they increase it at a lower rate than the growth in intermediate inputs. Consequently, it is worth emphasizing the potential environmental benefits of enhancing trade relations with these supplier partners, due to their efficiency in terms of GHG emissions.

On the other hand, the supplier partners located in the non-desirable states (strong negative decoupling, recessive negative decoupling, and weak negative decoupling) either contribute to increasing the PF of the EU-27's T&C industry or reduce it at a lower rate than the growth in intermediate inputs. Notably, Russia, Turkey, and RoW Middle East have achieved strong negative decoupling. The increase in GHG emissions, which is particularly worrying for supplier partners that reduced their production of inputs, indicates that the EI of the EU-27's T&C supply chain has become more polluting, especially in developing countries (Mair et al., 2016; Valodka et al., 2020).

The manufacturing phases are increasingly located outside the EU (Girneata and Dobrin, 2015; Valodka et al., 2020), but not all supplier partners increased their weight in the supply chain of the EU-27's final T&C producers. In general, the supplier partners registered a 36 % reduction in the provision of intermediate inputs for the EU-27's T&C supply chain, whereas their associated GHG emissions dropped by 28 % during the period analysed. China and India are worth highlighting as they present weak decoupling, despite their shares in the production of intermediate inputs increasing by 3865 % and 1446 %, respectively, during the analysed period. There are different reasons behind the decoupling achieved in these countries. In the case of China, industrial emissions controls were implemented during the analysed period, as

Table 1
Emission coefficient of the EU-27's T&C value chain by region for the period 1995–2022, expressed in megatons of CO_2 equivalent.

Region	EU-27	United Kingdom	China	India	Turkey	Indonesia	RoW
1995	4.85E-05	0.000102	0.000926	0.000332	1.41E-05	0.000104	6.67E-05
1996	4.93E-05	9.49E-05	0.000404	0.000451	1.38E-05	0.00012	0.000107
1997	4.76E-05	6.96E-05	0.000337	0.000302	1.62E-05	0.000174	8.16E-05
1998	4.51E-05	9.11E-05	0.000332	0.000392	1.78E-05	0.000309	9.4E-05
1999	4.32E-05	8.53E-05	0.000322	0.000292	3.52E-05	0.000227	8.97E-05
2000	4.49E-05	6.82E-05	0.000214	0.000229	4.85E-05	0.000182	6.94E-05
2001	4.25E-05	8.97E-05	0.000199	0.00019	4.44E-05	0.000316	8.29E-05
2002	4.4E-05	7.95E-05	0.000215	0.000162	9.43E-05	0.000214	7.36E-05
2003	4.91E-05	9.15E-05	0.000218	0.000145	8.5E-05	0.000182	8.69E-05
2004	4.48E-05	0.000104	0.000271	0.000158	0.000116	0.00031	8.29E-05
2005	3.5E-05	8.46E-05	0.000238	0.000152	3.8E-05	0.000357	7.33E-05
2006	3.38E-05	0.000104	0.000157	0.000125	3.54E-05	0.000226	6.51E-05
2007	2.89E-05	8.42E-05	0.00019	0.000107	2.25E-05	0.000219	6.9E-05
2008	2.78E-05	9.3E-05	0.000189	0.000137	1.1E-05	0.000209	6.12E-05
2009	2.63E-05	7.28E-05	0.000151	0.000105	4.98E-05	0.000242	6.22E-05
2010	2.5E-05	0.000155	0.000139	8.67E-05	2.31E-05	0.000123	7.72E-05
2011	2.33E-05	9.69E-05	0.000127	0.000144	5.84E-05	0.000148	7.5E-05
2012	2.16E-05	9.25E-05	8.87E-05	0.000158	6.05E-05	0.000189	7.46E-05
2013	2.22E-05	0.000118	8.48E-05	9.74E-05	6.28E-05	0.000188	9.16E-05
2014	2E-05	0.000135	6.77E-05	0.00015	7.11E-05	0.000192	9.2E-05
2015	1.99E-05	5.79E-05	5.89E-05	8.51E-05	0.000106	0.00021	9.72E-05
2016	2.15E-05	5.03E-05	5.22E-05	9.78E-05	0.000116	0.000158	0.000104
2017	2.16E-05	4.46E-05	4.85E-05	0.000107	0.000133	0.000141	0.000104
2018	2.12E-05	4.75E-05	3.9E-05	9.21E-05	0.000162	0.000168	0.000124
2019	2.29E-05	4.54E-05	3.25E-05	7.93E-05	0.000197	0.000131	0.00011
2020	2.45E-05	4.98E-05	3.11E-05	8.25E-05	0.000242	0.000108	0.000109
2021	1.68E-05	2.65E-05	2.39E-05	6.41E-05	0.000292	0.000108	6.99E-05
2022	1.65E-05	2.62E-05	2.4E-05	6.79E-05	0.000598	0.000134	7.24E-05

Source: *Own elaboration.*

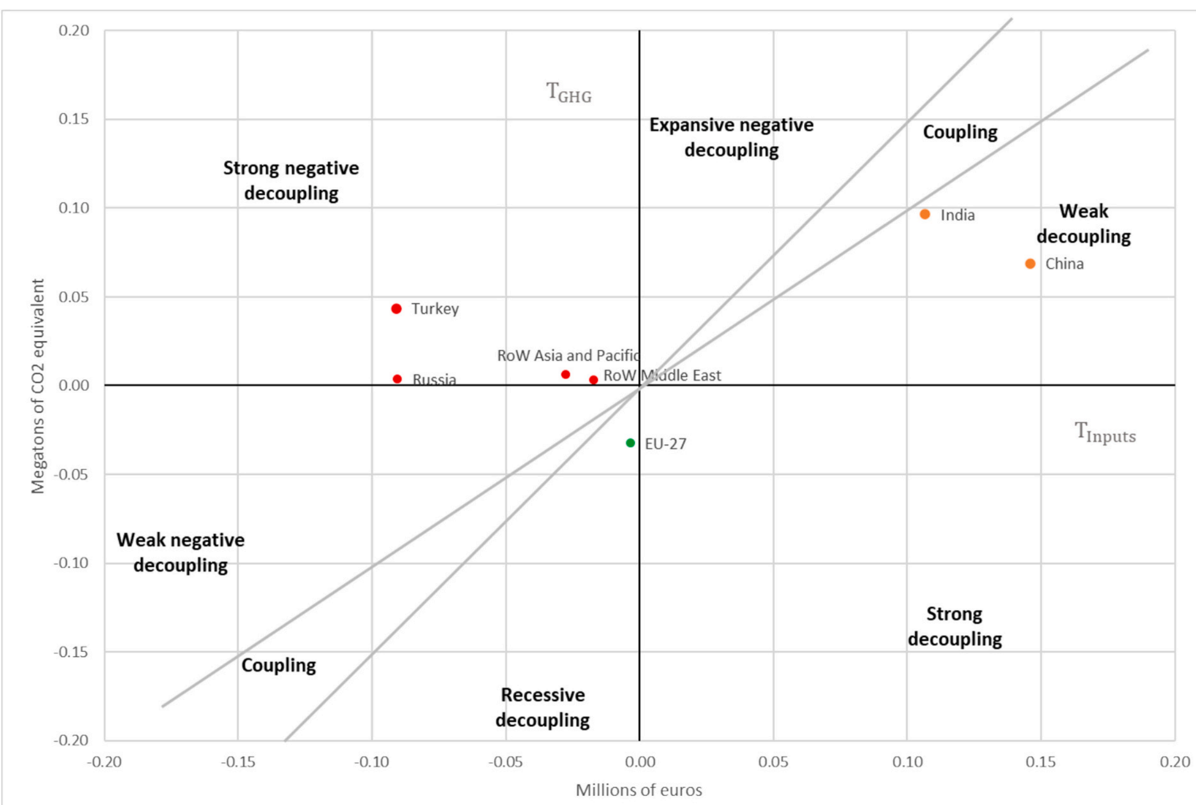

Fig. 5. Decoupling indices for the supply chain of the EU-27's final T&C producers by supplier partner during the period 1995–2022.

well as energy structure reform and the deployment of renewable energy (Feng and Fang, 2022). In the case of Taiwan, the voluntary GHG emissions reduction agreement was implemented (Chen and Hu, 2012), along with the government's regulatory measures to improve energy efficiency and renewable energy sources, which seems to have had a very positive effect (Tsai, 2021).

4. Conclusions

The EU is committed to enhancing sustainability and addressing the environmental impacts of the T&C industry, as reflected in the European Green Deal, the Circular Economy Action Plan, and the European Industrial Strategy. One key area of improvement is air pollution and GHG emissions, with the EU targeting levels that are not harmful to health and natural ecosystems. In the same vein, the EU aims to make production more sustainable and environmentally friendly, in part by improving the environmental impact of T&C supply chains and extending the life cycle of T&C products, regardless of where production occurs. To achieve the EU's objectives in this industry, a detailed understanding is needed of GHG emissions generation and where the hotspots occur along the supply chains of the EU-27's final T&C producers.

During the period analysed, the PF of the EU-27's T&C industry decreased by approximately 50 %, a drop which can be explained by the 61 % reduction in the DPF and the 27 % reduction in the EI. Both components of the DPF became cleaner in terms of GHG emissions; however, the generation of raw materials and inputs used by the EU-27's T&C industry were more polluting than the industry's own activity. Although fossil fuel power generation improved over the period, it remained the main source of GHG emissions, representing 33 % of the DPF in 2022. To continue reducing emissions, it is essential to develop technology that can improve the emission intensity, reduce the share of non-renewable energy and increase the share of renewable energy in the energy mix.

Regarding the EI, the share of these emissions in the PF of the EU-27's T&C industry increased by 15 %, indicating that the EU should implement import control measures to ensure the sustainable production of the EU-27's final T&C producers. Their supply chain is particularly dependent on the primary industries and energy sectors of supplier partners. Although the efficiency of supplier partners improved during the analysed period, some of their industries are more intensive in GHG emissions per unit of production than those of the EU-27, and are therefore a source of inefficiency.

Another issue that should be addressed is the increase in GHG emissions from transport activities as a result of the development of outsourcing strategies. In this regard, the EU should explore other less polluting transport options or technologies to make existing options more efficient in emissions. In addition, if T&C production were to take place in regions closer to the EU, or even with zero-kilometre supplier partners, the GHG emissions from transport could be further reduced.

By applying a system of sanctions and incentives, the EU can encourage companies to make investments to reduce pollution in third countries and to engage with like-minded partners in monitoring the sustainability and environmental impact of the T&C products imported into the region. For example, the energy sectors of supplier partners are a source of inefficiency that should be addressed by encouraging energy efficiency enhancements, and by improving renewable energy, since their energy mix tends to be more dependent on fossil fuel resources. Furthermore, it has been observed that the supplier partners' T&C industries are much more polluting in terms of GHG emissions than the EU-27's T&C industry; this should be considered a good reason for relocating the industry to Europe.

The EU-27's final T&C producers have made significant strides in decoupling GHG emissions from intermediate inputs, achieving a near-strong decoupling over the period from 1995 to 2022. During this time, there was a 9 % decrease in the intermediate inputs required in the supply chain of the EU-27's final T&C producers, while GHG emissions saw a substantial reduction of 59 %. This notable decrease in emissions is attributed to advancements in energy efficiency, electricity generation, and production techniques.

A diverse range of decoupling states was observed among supplier partners. Countries such as Switzerland, South Korea, RoW Europe, Australia, the United Kingdom, Canada, and the United States demonstrated the most significant decoupling of GHG emissions from intermediate inputs. Although these countries accounted for only 13 % of the EI in 2022, they represented 33 % of the intermediate inputs required by the EU-27's final T&C producers. Notably Russia, Turkey, and RoW Middle East achieved strong negative decoupling, with an increase in GHG emissions despite a reduction in intermediate input production, which suggests that the EU-27's T&C supply chain has become more polluting, particularly in developing countries. This finding highlights the potential environmental benefits of enhancing trade relations with energy-efficient supplier partners.

The decoupling analysis revealed that the EU-27 managed to decouple GHG emissions from intermediate inputs, with its T&C industry close to achieving strong decoupling during the period analysed. Its performance seems to be related to improvements in energy efficiency, electricity generation and production techniques. Supplier partners show a wide variety of decoupling states, but the increase in GHG emissions is particularly worrying in the case of countries that reduced the production of inputs during the period analysed, such as Norway or RoW Africa. China, India and Taiwan are noteworthy as they present weak decoupling, despite their marked increase in the share of intermediate inputs produced for the EU-27's T&C supply chain during the period.

Overall, this research contributes to a more complete understanding of GHG emissions generation in the supply chain of the EU-27's final T&C producers. In particular, it sheds light on the impact of each sector on emissions, and how these emissions have evolved over time. The results obtained can inform better strategies and policies to reduce GHG emissions from the EU-27's T&C industry.

CRediT authorship contribution statement

Luis Yamuza-Blanco: Writing – original draft, Investigation, Formal analysis. **Fabio Monsalve:** Writing – review & editing, Supervision, Software, Methodology, Data curation. **Rocío Román-Collado:** Writing – review & editing, Methodology, Conceptualization. **María Teresa Sanz-Díaz:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

A.1. Calculation of deflators

The multi-regional input-output tables from Exiobase have been deflated to 2008 constant prices to avoid the effect of price evolution. Deflation has been applied to intermediate inputs, gross value added and gross output data from Exiobase, with the process repeated for each data type. The deflation process combines sectorial World Input-Output Database (WIOD) deflators for desegregated categories from 1995 to 2014 and country GDP deflators from the World Bank and OECD National Accounts from 2015 to 2022, due to the data limitations of Exiobase.

The WIOD database provides two sets of deflators, one for 40 regions and 35 industries for the period from 1995 to 2000, and another for 43 regions and 56 industries for the period from 2000 to 2014. These two datasets of deflators have been transformed into EXIOBASE region and product classification by a data duplication process following the EXIOBASE Concordance Tables. The correspondence between the regions in the EXIOBASE and the two WIOD classifications can be seen in the tables below[1]:

Table A1
Correspondence between regions in the EXIOBASE database and WIOD database from 1995 to 2000.

EXIOBASE		WIOD (1995–2000)	
AUT	Austria	AUT	Austria
BEL	Belgium	BEL	Belgium
BGR	Bulgaria	BGR	Bulgaria
CYP	Cyprus	CYP	Cyprus
CZE	Czech Republic	CZE	Czech Republic
DEU	Germany	DEU	Germany
DNK	Denmark	DNK	Denmark
EST	Estonia	EST	Estonia
ESP	Spain	ESP	Spain
FIN	Finland	FIN	Finland
FRA	France	FRA	France
GRC	Greece	GRC	Greece
HRV	Croatia	SVN	Slovenia
HUN	Hungary	HUN	Hungary
IRL	Ireland	IRL	Ireland
ITA	Italy	ITA	Italy
LTU	Lithuania	LTU	Lithuania
LUX	Luxembourg	LUX	Luxembourg
LVA	Latvia	LVA	Latvia
MLT	Malta	MLT	Malta
NLD	Netherlands	NLD	Netherlands
POL	Poland	POL	Poland
PRT	Portugal	PRT	Portugal
ROU	Romania	ROU	Romania
SWE	Sweden	SWE	Sweden
SVN	Slovenia	SVN	Slovenia
SVK	Slovakia	SVK	Slovakia
GBR	United Kingdom	GBR	United Kingdom
USA	United States	USA	United States
JPN	Japan	JPN	Japan
CHN	China	CHN	China
CAN	Canada	CAN	Canada
KOR	South Korea	KOR	South Korea
BRA	Brazil	BRA	Brazil
IND	India	IND	India
MEX	Mexico	MEX	Mexico
RUS	Russia	RUS	Russia
AUS	Australia	AUS	Australia
CHE	Switzerland	LUX	Luxembourg
TUR	Turkey	TUR	Turkey
TWN	Taiwan	TWN	Taiwan
NOR	Norway	FIN	Finland
IDN	Indonesia	IDN	Indonesia
ZAF	South Africa	BRA	Brazil
WA	RoW Asia and Pacific	MEX	Mexico
WL	RoW America	MEX	Mexico
WE	RoW Europe	MEX	Mexico
WF	RoW Africa	MEX	Mexico
WM	RoW Middle East	MEX	Mexico

[1] In order to replicate the countries that are not in the WIOD, countries in a similar economic situation have been chosen, on the basis of economic indicators such as GDP.

Table A2
Correspondence between regions in the EXIOBASE database and WIOD database from 2000 to 2014.

EXIOBASE		WIOD (2000–2014)	
AUT	Austria	AUT	Austria
BEL	Belgium	BEL	Belgium
BGR	Bulgaria	BGR	Bulgaria
CYP	Cyprus	CYP	Cyprus
CZE	Czech Republic	CZE	Czech Republic
DEU	Germany	DEU	Germany
DNK	Denmark	DNK	Denmark
EST	Estonia	EST	Estonia
ESP	Spain	ESP	Spain
FIN	Finland	FIN	Finland
FRA	France	FRA	France
GRC	Greece	GRC	Greece
HRV	Croatia	HRV	Croatia
HUN	Hungary	HUN	Hungary
IRL	Ireland	IRL	Ireland
ITA	Italy	ITA	Italy
LTU	Lithuania	LTU	Lithuania
LUX	Luxembourg	LUX	Luxembourg
LVA	Latvia	LVA	Latvia
MLT	Malta	MLT	Malta
NLD	Netherlands	NLD	Netherlands
POL	Poland	POL	Poland
PRT	Portugal	PRT	Portugal
ROU	Romania	ROU	Romania
SWE	Sweden	SWE	Sweden
SVN	Slovenia	SVK	Slovakia
SVK	Slovakia	SVN	Slovenia
GBR	United Kingdom	GBR	United Kingdom
USA	United States	USA	United States
JPN	Japan	JPN	Japan
CHN	China	CHN	China
CAN	Canada	CAN	Canada
KOR	South Korea	KOR	South Korea
BRA	Brazil	BRA	Brazil
IND	India	IND	India
MEX	Mexico	MEX	Mexico
RUS	Russia	RUS	Russia
AUS	Australia	AUS	Australia
CHE	Switzerland	CHE	Switzerland
TUR	Turkey	TUR	Turkey
TWN	Taiwan	TWN	Taiwan
NOR	Norway	NOR	Norway
IDN	Indonesia	IDN	Indonesia
ZAF	South Africa	MEX	Mexico
WA	RoW Asia and Pacific	MEX	Mexico
WL	RoW America	MEX	Mexico
WE	RoW Europe	MEX	Mexico
WF	RoW Africa	MEX	Mexico
WM	RoW Middle East	MEX	Mexico

The country GDP deflators from the World Bank and OECD National Accounts provide a set of country deflators for the period from 2005 to 2022. This dataset of deflators has been transformed into EXIOBASE region and product classification by a data duplication process following the EXIOBASE Concordance Tables and structure.

The deflation process involves two operations. The first is the chaining of databases by index numbers to 2008 base year. The second is the deflation operation, which consist in multiplying the input-output tables by the following deflation index:

$$\overline{p_{2008}} = \frac{p_x}{p_{2008}}$$

Appendix B

Table B1
The ten most polluting industries in terms of emissions imported of the EU-27's T&C industry in 2022, expressed in megatons of CO_2 equivalent.

Industry	Supplier partner	EI
Production of electricity by coal	China	4.4959128
Meat animals nec	Turkey	1.27867353
Extraction of natural gas and services related to natural gas extraction, excluding surveying	Russia	0.922168874
Extraction of crude petroleum and services related to crude oil extraction, excluding surveying	RoW Middle East	0.692534849
Production of electricity by coal	India	0.683719161
Production of electricity by coal	Turkey	0.599042865
Manufacture of basic iron and steel and of ferro-alloys and first products thereof	China	0.558575991
Extraction of crude petroleum and services related to crude oil extraction, excluding surveying	RoW Asia and Pacific	0.550051379
Production of electricity by coal	RoW Asia and Pacific	0.477174985
Production of electricity by coal	RoW Europe	0.473043944

Source: *Own elaboration.*

Data availability

Data will be made available on request.

References

Adler, U., 2004. Structural change: the dominant feature in the economic development of the German textile and clothing industries. J. Fash. Mark. Manag. 8 (3), 300–319. https://doi.org/10.1108/13612020410547815.

Alpkokin, P., Black, J.A., Iyinam, S., Kesten, A.S., 2016. Historical analysis of economic, social and environmental impacts of the Europe-Asia crossings in Istanbul. Int. J. Sustain. Transp. 10 (2), 65–75. https://doi.org/10.1080/15568318.2013.853852.

Al-Tohamy, R., Ali, S.S., Li, F., Okasha, K.M., Mahmoud, Y.A.-G., Elsamahy, T., Jiao, H., Fu, Y., Sun, J., 2022. A critical review on the treatment of dye-containing wastewater: Ecotoxicological and health concerns of textile dyes and possible remediation approaches for environmental safety. Ecotoxicol. Environ. Saf. 231, 113160. https://doi.org/10.1016/j.ecoenv.2021.113160.

Amicarelli, V., Bux, C., Spinelli, M.P., Lagioia, G., 2022. Life cycle assessment to tackle the take-make-waste paradigm in the textiles production. https://doi.org/10.1016/j.wasman.2022.07.032.

Amutha, K., 2017. Sustainable chemical management and zero discharges. In: Sustainable Fibres and Textiles. Elsevier, pp. 347–366. https://doi.org/10.1016/B978-0-08-102041-8.00012-3.

Andrew, R., Peters, G.P., Lennox, J., 2009. Approximation and regional aggregation in multiregional input-output analysis for national carbon footprint accounting. Econ. Syst. Res. 21 (3), 311–335. https://doi.org/10.1080/09535310903541751.

Assogbavi, K.K.E., Dées, S., 2023. Environmental policy and the CO2 emissions embodied in international trade. Environ. Resour. Econ. 84 (2), 507–527. https://doi.org/10.1007/S10640-022-00734-6.

Azad, R., Chakraborty, S., 2023. An Indian Green Deal. *Ecological Economics* 209, 107830. https://doi.org/10.1016/j.ecolecon.2023.107830.

Baajike, F.B., Oteng-Abayie, E.F., Dramani, J.B., Amanor, K., 2024. Effects of trade liberalization on the global decoupling and decomposition of CO2 emissions from economic growth. Heliyon 10 (1), e23470. https://doi.org/10.1016/j.heliyon.2023.e23470.

Barrientos, S., Gereffi, G., Pickles, J., 2016. New dynamics of upgrading in global value chains: shifting terrain for suppliers and workers in the global south. Environment and Planning A: Economy and Space 48 (7), 1214–1219. https://doi.org/10.1177/0308518X16634160.

Bauer, F., Tilsted, J.P., Pfister, S., Oberschelp, C., Kulionis, V., 2023. Mapping GHG emissions and prospects for renewable energy in the chemical industry. Curr. Opin. Chem. Eng. 39, 100881. https://doi.org/10.1016/J.COCHE.2022.100881.

Beton, A., Dias, D., Farrant, L., Gibon, T., Le Guern, Y., Desaxce, M., Perwueltz, A., Boufateh, I., Wolf, O., Kougoulis, J., Cordella, M., Dodd, N., 2014. Environmental improvement potential of textiles (IMPRO textiles). Report EUR 26316 EN, issue (January). https://doi.org/10.2791/52624.

Bhar, S., Lele, S., Min, J., Rao, N.D., 2024. Water, air pollution and carbon footprints of conspicuous/luxury consumption in India. Ecol. Econ. 218, 108104. https://doi.org/10.1016/j.ecolecon.2024.108104.

Blancheton, B., 2021. French fashion and textile during COVID-19. Once again, flying to high quality and innovation to survive. Fash. Text. 8 (1), 1–13. https://doi.org/10.1186/s40691-021-00278-1.

Bonilla, D., Keller, H., Schmiele, J., 2015. Climate policy and solutions for green supply chains: Europe's predicament. Supply Chain Management: An International Journal 20 (3), 249–263. https://doi.org/10.1108/SCM-05-2014-0171.

Brunel, C., 2014. Pollution offshoring and emission reductions in EU and US manufacturing. SSRN Electron. J. https://doi.org/10.2139/ssrn.2447679.

Chen, X., 2023. Reconnecting Eurasia: a new logistics state, the China–Europe freight train, and the resurging ancient city of Xi'an. Eurasian Geogr. Econ. 64 (1), 60–88. https://doi.org/10.1080/15387216.2021.1980075.

Chen, L.-T., Hu, A.H., 2012. Voluntary GHG reduction of industrial sectors in Taiwan. Chemosphere 88 (9), 1074–1082. https://doi.org/10.1016/j.chemosphere.2012.04.049.

Claudio, L., 2007. Waste couture: Environmental impact of the clothing industry. Environmental Health Perspectives 115 (9). https://doi.org/10.1289/EHP.115-A449.

Curran, L., Zignago, S., 2010. The financial crisis: impact on key clothing markets and suppliers. Journal of Fashion Marketing and Management: An International Journal 14 (4), 530–545. https://doi.org/10.1108/13612021011081724.

de Oliveira Neto, G.C., Tucci, H.N.P., Correia, J.M.F., da Silva, P.C., da Silva, V.H.C., Ganga, G.M.D., 2020. Assessing the implementation of cleaner production and company sizes: survey in textile companies. Journal of Engineered Fibers and Fabrics 15, 155892502091558. https://doi.org/10.1177/1558925020915585.

Diddi, S., Yan, R.-N., Bloodhart, B., Bajtelsmit, V., McShane, K., 2019. Exploring young adult consumers' sustainable clothing consumption intention-behavior gap: a behavioral reasoning theory perspective. Sustainable Production and Consumption 18, 200–209. https://doi.org/10.1016/j.spc.2019.02.009.

Directive 2010/75/EU of the European Parliament and of the Council, 2010. On industrial emissions (integrated pollution prevention and control). Official Journal of the European Union, L 334, 17. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32010L0075.

Directive 2012/27/EU of the European Parliament and of the Council, 2012. On energy efficiency, amending directives 2009/125/EC and 2010/30/ EU and repealing directives 2004/8/EC and 2006/32/EC. Official Journal of the European Union, L 3 (15/1), 14. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32012L0027.

Duarte, R., Serrano, A., 2021. Environmental analysis of structural and technological change in a context of trade expansion: lessons from the EU enlargement. Energy Policy 150, 112142. https://doi.org/10.1016/J.ENPOL.2021.112142.

Dunford, M., 2004. The Changing Profile and Map of the EU Textile and Clothing Industry. European Industrial Restructuring in a Global Economy, Fragmentation and Relocation of Value Chains. https://www.researchgate.net/publication/228846153_The_changing_profile_and_map_of_the_EU_textile_and_clothing_industry.

EC (European Commission), 1995a. No 3030/93 on common rules for imports of certain textile products from third countries. http://data.europa.eu/eli/reg/1995/3053/oj.

EC (European Commission), 1995b. No 3036/94 establishing economic outward processing arrangements applicable to certain textile and clothing products reimported into the Community after working or processing in certain third countries. http://data.europa.eu/eli/reg/1995/3017/oj.

EC (European Commission), 1996a. Community quantitative limits on re-importation into the European Community of certain textile products originating in the People's Republic of China after outward processing operations in that country. http://data.europa.eu/eli/reg/1996/1406/oj.

EC (European Commission), 1996b. No 517/94 on common rules for imports of textile products from certain third countries. http://data.europa.eu/eli/reg/1996/1476/oj.

EC (European Commission), 1996c. No 2635/95 introducing prior surveillance of imports of certain textile products originating in the United Arab Emirates. http://data.europa.eu/eli/reg/1996/941/oj.

EC (European Commission), 1996d. No 93/96 of 23 January 1996 deducting from the quantitative limits on imports of certain categories of textile products originating in the People's Republic of China amounts corresponding to those imported into the European Community in circumvention of the Agreement between the European Community and the People's Republic of China on trade in textile products. http://data.europa.eu/eli/reg/1996/93/oj.

EC (European Commission), 2003. Integrated Pollution Prevention and Control (IPPC). Reference document on best available techniques for the textiles industry. https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/txt_bref_0703.pdf.

EC (European Commission), 2015. Report from the commission to the European Parliament and the Council. Assessment of the progress made by Member States towards the national energy efficiency targets for 2020 and towards the implementation of the Energy Efficiency Directive 2012/27/EU as required by article 24 (3) of Energy Efficiency Directive 2012/27/EU. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52015SC0245&qid=1710164735719.

EC (European Commission), 2017a. Report from the Commission to the European Parliament and the Council. 2017 assessment of the progress made by Member States towards the national energy efficiency targets for 2020 and towards the implementation of the Energy Efficiency Directive as required by article 24 (3) of the Energy Efficiency Directive 2012/27/EU. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52017DC0687&qid=1710164735719.

EC (European Commission), 2017b. Report from the Commission to the European Parliament and the Council. 2016 assessment of the progress made by Member States in 2014 towards the national energy efficiency targets for 2020 and towards the implementation of the Energy Efficiency Directive 2012/27/EU as required by article 24 (3) of the Energy Efficiency Directive 2012/27/EU. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52017DC0056&qid=1710164735719.

EC (European Commission), 2019. Report from the Commission to the European Parliament and the Council. 2018 assessment of the progress made by Member States towards the national energy efficiency targets for 2020 and towards the implementation of the Energy Efficiency Directive as required by article 24 (3) of the Energy Efficiency Directive 2012/27/EU. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0224&qid=1710164735719.

EC (European Commission), 2020. Report from the Commission to the European Parliament and the Council. 2019 assessment of the progress made by member states towards the national energy efficiency targets for 2020 and towards the implementation of the Energy Efficiency Directive as required by article 24 (3) of the Energy Efficiency Directive 2012/27/EU. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0326&qid=1710164735719.

EC (European Commission), 2024a. The European Green Deal. Striving to be the first climate-neutral continent. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.

EC (European Commission), 2024b. Circular economy action plan. https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en.

EC (European Commission), 2024c. European industrial strategy. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/european-industrial-strategy_en.

EC (European Commission), 2024d. Zero pollution action plan. https://environment.ec.europa.eu/strategy/zero-pollution-action-plan_en.

EC (European Commission), 2024e. About sustainable products. https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/ecodesign-sustainable-products-regulation_en.

EC (European Commission), 2024f. 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.

EC (European Commission), 2024g. EU strategy for sustainable and circular textiles. https://environment.ec.europa.eu/strategy/textiles-strategy_en.

EEA (European Environment Agency), 2023. Textiles in Europe's circular economy. https://www.eea.europa.eu/publications/textiles-in-europes-circular-economy.

(Ellen Macarthur Foundation), EMF. A new textiles economy: redesigning fashion's future. https://www.ellenmacarthurfoundation.org/a-new-textiles-economy.

EMF (Ellen Macarthur Foundation), 2021. Circular business models: Redefining growth for a thriving fashion industry. https://www.ellenmacarthurfoundation.org/news/circular-business-models-in-the-fashion-industry.

EP (European Parliament), 2023a. Climate change: the greenhouse gases causing global warming. https://www.europarl.europa.eu/news/en/headlines/society/20230316STO77629/climate-change-the-greenhouse-gases-causing-global-warming.

EP (European Parliament), 2023b. Parliament wants to make EU textiles and clothing industry greener. https://www.europarl.europa.eu/news/en/press-room/20230524IPR91913/parliament-wants-to-make-eu-textiles-and-clothing-industry-greener.

EP (European Parliament), 2023c. Ending fast fashion: tougher rules to fight excessive production and consumption. https://www.europarl.europa.eu/news/en/press-room/20230424IPR82040/ending-fast-fashion-tougher-rules-to-fight-excessive-production-and-consumption.

EPC (European Parliament and Council), 2008. Directive 2008/1/EC of the parliament and the council of 15 January 2008 concerning integrated pollution prevention and control (codified version). Official journal of the European Union L 24, 8–29. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0001&from=EN.

Eskander, S.M.S.U., Fankhauser, S., 2023. The impact of climate legislation on trade-related carbon emissions 1996–2018. Environ. Resour. Econ. 85 (1), 167–194. https://doi.org/10.1007/S10640-023-00762-W.

EURATEX, 2020. The textile and clothing industry in 2020: Facts and key figures. https://euratex.eu/facts-and-key-figures/.

EURATEX, 2022. The textile and clothing industry in 2022: Facts and key figures. https://euratex.eu/facts-and-key-figures/.

Eurostat, 2008. NACE Rev. 2 – Statistical classification of economic activities in the European Community. *Office for Official Publications of the European Communities*, 141–145. https://ec.europa.eu/eurostat/web/products-manuals-and-guidelines/-/ks-ra-07-015.

Eurostat, 2024. International trade in goods – detailed data. EU trade since 2002 by CPA 2.1. https://ec.europa.eu/eurostat/en/.

EXIOBASE, 2023. Exiobase data concordances. https://www.exiobase.eu/.

Feng, R., Fang, X., 2022. China's pathways to synchronize the emission reductions of air pollutants and greenhouse gases: pros and cons. Resour. Conserv. Recycl. 184, 106392. https://doi.org/10.1016/j.resconrec.2022.106392.

Gao, Z., Geng, Y., Wu, R., Zhang, X., Pan, H., Jiang, H., 2020. China's CO2 emissions embodied in fixed capital formation and its spatial distribution. Environ. Sci. Pollut. Res. 27 (16), 19970–19990. https://doi.org/10.1007/S11356-020-08491-Z.

García-Alaminos, Á., Monsalve, F., Zafrilla, J., Cadarso, M.A., 2020. Unmasking social distant damage of developed regions' lifestyle: a decoupling analysis of the indecent labour footprint. PLoS One 15 (4), e0228649. https://doi.org/10.1371/JOURNAL.PONE.0228649.

Giri, S., Shankar Rai, S., 2013. Dynamics of garment supply chain. International Journal of Managing Value and Supply Chains 4 (4), 29–42. https://doi.org/10.5121/ijmvsc.2013.4403.

Girneata, A., Dobrin, C., 2015. Globalization and the competitiveness of the European textile and clothing industry. https://www.researchgate.net/publication/299089272.

Harsányi, E., Bashir, B., Almhamad, G., Hijazi, O., Maze, M., Elbeltagi, A., Alsalman, A., Enaruvbe, G.O., Mohammed, S., Szabó, S., 2021. GHGs emission from the agricultural sector within EU-28: a multivariate analysis approach. *Energies 2021, Vol. 14, page 6495*, *14*(20), 6495. https://doi.org/10.3390/EN14206495.

Haseeb, M., Haouas, I., Nasih, M., Mihardjo, L.W.W., Jermsittiparsert, K., 2020. Asymmetric impact of textile and clothing manufacturing on carbon-dioxide emissions: evidence from top Asian economies. Energy 196, 117094. https://doi.org/10.1016/j.energy.2020.117094.

Hobson, K., 2016. Closing the loop or squaring the circle? Locating generative spaces for the circular economy. Prog. Hum. Geogr. 40 (1), 88–104. https://doi.org/10.1177/0309132514566342.

Hoekstra, R., 2010. (towards) a complete database of peer-reviewed articles on environmentally extended input-output analysis. Statistics Netherlands 2010–2137. https://www.researchgate.net/publication/309398399_Towards_a_complete_database_of_peer-reviewed_articles_on_environmentally_extended_input-output_analysis.

Hole, G., Hole, A.S., 2019. Recycling as the way to greener production: a mini review. J. Clean. Prod. 212, 910–915. https://doi.org/10.1016/j.jclepro.2018.12.080.

Hong, L., Liu, X., Liu, B., Cao, K., Xia, Q., 2024. The impact of reducing trade barriers on enterprises' pollution emissions: evidence from China. Manag. Decis. Econ. https://doi.org/10.1002/MDE.4087.

Hrouga, M., Michel, S., 2023. Towards a new supply chain manager dashboard under circular economy constraints: a case study on France textile and clothing industry. Bus. Strateg. Environ. 32 (8), 6074–6093. https://doi.org/10.1002/bse.3473.

Huang, B., Zhao, J., Geng, Y., Tian, Y., Jiang, P., 2017. Energy-related GHG emissions of the textile industry in China. Resour. Conserv. Recycl. 119, 69–77. https://doi.org/10.1016/j.resconrec.2016.06.013.

Huang, Q., Zhang, X., Li, Y., 2023. Study on the economic effects of China and ASEAN countries from the new international Land-Sea trade corridor. Transp. Policy 139, 123–135. https://doi.org/10.1016/J.TRANPOL.2023.05.005.

Imran, S., Mujtaba, M.A., Zafar, M.M., Hussain, A., Mehmood, A., Farwa, U.E., Korakianitis, T., Kalam, M.A., Fayaz, H., Saleel, C.A., 2023. Assessing the potential of GHG emissions for the textile sector: a baseline study. Heliyon 9 (11), e22404. https://doi.org/10.1016/j.heliyon.2023.e22404.

IPCC (Intergovernmental Panel on Climate Change), 2014. Anthropogenic and natural radiative forcing. In: Climate Change 2013 – The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, vol. 9781107057999. Cambridge University Press, pp. 659–740. https://doi.org/10.1017/CBO9781107415324.018.

Islam, M., Kanemoto, K., Managi, S., 2016. Impact of trade openness and sector trade on embodied greenhouse gases emissions and air pollutants. J. Ind. Ecol. 20 (3), 494–505. https://doi.org/10.1111/JIEC.12455.

Jiang, Y., Qiao, G., Lu, J., 2020. Impacts of the New International Land–Sea Trade Corridor on the Freight Transport Structure in China, Central Asia, the ASEAN countries and the EU. Res. Transp. Bus. Manag. 35, 100419. https://doi.org/10.1016/J.RTBM.2019.100419.

Kanemoto, K., Lenzen, M., Peters, G.P., Moran, D.D., Geschke, A., 2012. Frameworks for comparing emissions associated with production, consumption, and international trade. Environ. Sci. Technol. 46 (1), 172–179. https://doi.org/10.1021/es202239t.

Keenan, M., Saritas, O., Kroener, I., 2004. A dying industry – or not? The future of the European textiles and clothing industry. Foresight 6 (5), 313–322. https://doi.org/10.1108/14636680410563016.

Kozlowski, A., Searcy, C., Bardecki, M., 2016. Innovation for a sustainable fashion industry: a design focused approach toward the development of new business models. Environmental Footprints and Eco-Design of Products and Processes 151–169. https://doi.org/10.1007/978-981-10-0245-8_5.

Kumar, L., Kamil, I., Ahmad, M., Naqvi, S.A., Deitch, M.J., Amjad, A.Q., Kumar, A., Basheer, S., Arshad, M., Sassanelli, C., 2022. In-house resource efficiency improvements supplementing the end of pipe treatments in textile SMEs under a circular economy fashion. Front. Environ. Sci. 10. https://doi.org/10.3389/fenvs.2022.1002319.

Leal Filho, W., Perry, P., Heim, H., Dinis, MAP., Moda, H., Ebhuoma, E., Paço, A., 2022. An overview of the contribution of the textiles sector to climate change. Front. Environ. Sci. 10, 973102. https://doi.org/10.3389/fenvs.2022.973102.

Liang, Y., Zhong, Q., Deng, Z., Li, H., Jetashree, Yang, Z., & Liang, S., 2023. Multiperspective decoupling analyses between global embodied carbon chains and global value chains. Environ. Sci. Technol. 57 (48), 19690–19701. https://doi.org/10.1021/acs.est.3c06715.

López, L.-A., Cadarso, M.-Á., Zafrilla, J., Arce, G., 2019. The carbon footprint of the U.S. multinationals' foreign affiliates. *Nature*. Communications 10 (1), 1672. https://doi.org/10.1038/s41467-019-09473-7.
Mair, S., Druckman, A., Jackson, T., 2016. Global inequities and emissions in Western European textiles and clothing consumption. J. Clean. Prod. 132, 57–69. https://doi.org/10.1016/j.jclepro.2015.08.082.
Malik, A., Lafortune, G., Carter, S., Li, M., Lenzen, M., Kroll, C., 2021. International spillover effects in the EU'S textile supply chains: a global SDG assessment. J. Environ. Manag. 295, 113037. https://doi.org/10.1016/j.jenvman.2021.113037.
Manda, B.M.K., Worrell, E., Patel, M.K., 2015. Prospective life cycle assessment of an antibacterial T-shirt and supporting business decisions to create value. Resour. Conserv. Recycl. 103, 47–57. https://doi.org/10.1016/j.resconrec.2015.07.010.
Martínez-Mora, C., Merino, F., 2021. Extending the offshoring literature to explain backshoring: an application to the Spanish footwear industry. Growth Chang. 52 (3), 1230–1250. https://doi.org/10.1111/grow.12498.
McCarthy, I., Anagnostou, A., 2004. The impact of outsourcing on the transaction costs and boundaries of manufacturing. Int. J. Prod. Econ. 88 (1), 61–71. https://doi.org/10.1016/S0925-5273(03)00183-X.
Miller, R.E., Blair, P.D., 2009. Input-Output Analysis. Foundations and Extensions, Second Edition. Cambridge University Press, In Input-Output Analysis. https://doi.org/10.1017/CBO9780511626982.
Minx, J.C., Wiedmann, T., Wood, R., Peters, G.P., Lenzen, M., Owen, A., Scott, K., Barrett, J., Hubacek, K., Baiocchi, G., Paul, A., Dawkins, E., Briggs, J., Guan, D., Suh, S., Ackerman, F., 2009. Input–output analysis and carbon FOOTPRINTING: an overview of applications. Econ. Syst. Res. 21 (3), 187–216. https://doi.org/10.1080/09535310903541298.
Mohammed, S., Alsafadi, K., Takács, I., Harsányi, E., 2020. Contemporary changes of greenhouse gases emission from the agricultural sector in the EU-27. Geology, Ecology, and Landscapes 4 (4), 282–287. https://doi.org/10.1080/24749508.2019.1694129.
Mohiuddin, M., Rashid, M.D.M., al Azad, MD. S., & Su, Z., 2019. Back-shoring or re-shoring: determinants of manufacturing offshoring from emerging to least developing countries (LDCs). Int J Log Res Appl 22 (1), 78–97. https://doi.org/10.1080/13675567.2018.1475554.
Nepal, R., Musibau, H.O., Jamasb, T., 2021. Energy consumption as an indicator of energy efficiency and emissions in the European Union: a GMM based quantile regression approach. Energy Policy 158, 112572. https://doi.org/10.1016/J.ENPOL.2021.112572.
Nimkar, U., 2018. Sustainable chemistry: a solution to the textile industry in a developing world. Current Opinion in Green and Sustainable Chemistry 9, 13–17. https://doi.org/10.1016/J.COGSC.2017.11.002.
Olsen, K. B., Ibsen, R., & Westergaard-Nielsen, N. (2004). Does outsourcing create unemployment? The Case of the Danish Textile and Clothing Industry. Working paper 0003196. ISSN 1397-4831. https://pure.au.dk/portal/en/publications/does-outsourcing-create-unemployment-the-case-of-the-danish-texti.
Ortiz, M., Cadarso, M., López, L., 2020a. The carbon footprint of foreign multinationals within the European Union. J. Ind. Ecol. 24 (6), 1287–1299. https://doi.org/10.1111/jiec.13017.
Ortiz, M., López, L.-A., Cadarso, M., 2020b. EU carbon emissions by multinational enterprises under control-based accounting. Resour. Conserv. Recycl. 163, 105104. https://doi.org/10.1016/j.resconrec.2020.105104.
Ozturk, H.K., 2005. Energy usage and cost in textile industry: a case study for Turkey. Energy 30 (13), 2424–2446. https://doi.org/10.1016/j.energy.2004.11.014.
Ozturk, I., Majeed, M.T., Khan, S., 2021. Decoupling and decomposition analysis of environmental impact from economic growth: a comparative analysis of Pakistan, India, and China. Environ. Ecol. Stat. 28 (4), 793–820. https://doi.org/10.1007/S10651-021-00495-3.
Pal, R., Gander, J., 2018. Modelling environmental value: an examination of sustainable business models within the fashion industry. J. Clean. Prod. 184, 251–263. https://doi.org/10.1016/j.jclepro.2018.02.001.
Palamutcu, S., 2010. Electric energy consumption in the cotton textile processing stages. Energy 35 (7), 2945–2952. https://doi.org/10.1016/j.energy.2010.03.029.
Pandey, D., Agrawal, M., Pandey, J.S., 2011. Carbon footprint: current methods of estimation. Environ. Monit. Assess. 178 (1–4), 135–160. https://doi.org/10.1007/s10661-010-1678-y.
Payet, J., 2021. Assessment of carbon footprint for the textile sector in France. Sustainability 13 (5), 2422. https://doi.org/10.3390/su13052422.
Peng, B., Streimikiene, D., Agnusdei, G.P., Balezentis, T., 2024. Is sustainable energy development ensured in the EU agriculture? Structural shifts and the energy-related greenhouse gas emission intensity. J. Clean. Prod. 445, 141325. https://doi.org/10.1016/J.JCLEPRO.2024.141325.
Peters, G., Svanström, M., Roos, S., Sandin, G., Zamani, B., 2015. Carbon footprints in the textile industry. *Handbook of life cycle assessment (LCA) of textiles and clothing*, 3–30. https://doi.org/10.1016/B978-0-08-100169-1.00001-0.
Peters, G., Li, M., Lenzen, M., 2021. The need to decelerate fast fashion in a hot climate - a global sustainability perspective on the garment industry. J. Clean. Prod. 295, 126390. https://doi.org/10.1016/j.jclepro.2021.126390.
Rodrigues, J.F.D., Wang, J., Behrens, P., de Boer, P., 2020. Drivers of CO2 emissions from electricity generation in the European Union 2000–2015. Renew. Sust. Energ. Rev. 133, 110104. https://doi.org/10.1016/J.RSER.2020.110104.
Román-Collado, R., Sanz-Díaz, M.T., Loja Pacheco, C., 2021. Towards the decarbonisation of Ecuador: a multisectoral and multiregional analysis of its carbon footprint. Environ. Sci. Pollut. Res. Int. 28 (38), 53412–53431. https://doi.org/10.1007/s11356-021-14521-1.
Román-Collado, R., Sanz-Díaz, M.T., Yamuza Blanco, L., 2023. Key drivers of the textile and clothing industry decarbonisation within the EU-27. J. Environ. Manag. 334, 117438. https://doi.org/10.1016/J.JENVMAN.2023.117438.
Saha, K., Dey, P.K., Papagiannaki, E., 2021. Implementing circular economy in the textile and clothing industry. Bus. Strateg. Environ. 30 (4), 1497–1530. https://doi.org/10.1002/bse.2670.
Sanyé-Mengual, E., Secchi, M., Corrado, S., Beylot, A., Sala, S., 2019. Assessing the decoupling of economic growth from environmental impacts in the European Union: a consumption-based approach. J. Clean. Prod. 236, 117535. https://doi.org/10.1016/J.JCLEPRO.2019.07.010.
Scarlat, N., Prussi, M., Padella, M., 2022. Quantification of the carbon intensity of electricity produced and used in Europe. Appl. Energy 305, 117901. https://doi.org/10.1016/J.APENERGY.2021.117901.
Schwörer, T., 2013. Offshoring, domestic outsourcing and productivity: evidence for a number of European countries. Rev. World Econ. 149 (1), 131–149. https://doi.org/10.1007/s10290-012-0139-9.
Serweta, W., Gajewski, R., Olszewski, P., Zapatero, A., Ławińska, K., 2019. Carbon footprint of different kinds of footwear – a comparative study. Fibres and Textiles in Eastern Europe 27 (5(137)), 140–149. https://www.researchgate.net/publication/336924621_Carbon_Footprint_of_Different_Kinds_of_Footwear_-_a_Comparative_Study.
Shen, J., Smith, E., 2015. Enzymatic treatments for sustainable textile processing. In: Sustainable Apparel. Elsevier, pp. 119–133. https://doi.org/10.1016/B978-1-78242-339-3.00004-2.
Stadler, K., Wood, R., Bulavskaya, T., Södersten, C., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J.H., Theurl, M.C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K., Tukker, A., 2018. EXIOBASE 3: developing a time series of detailed environmentally extended multi-regional input-output tables. J. Ind. Ecol. 22 (3), 502–515. https://doi.org/10.1111/jiec.12715.
Stengg, W., 2001. The textile and clothing industry in EU. Textile Forum Enterprise papers 2. https://edz.bib.uni-mannheim.de/www-edz/pdf/entpap/ep-02-2001.pdf.
Stridsland, T., Bjørnstad, W., Vigen, K., Østergaard, K.L., Sanderson, H., 2023. No-one left behind: an open access approach to estimating the carbon footprint of a Danish clothing company. J. Clean. Prod. 426, 139126. https://doi.org/10.1016/j.jclepro.2023.139126.
Suh, S., 2009. *Handbook of input-output economics in industrial ecology* (S. Suh, Ed.; Vol. 23). Springer Netherlands. https://doi.org/10.1007/978-1-4020-5737-3.
Tapio, P., 2005. Towards a theory of decoupling: degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. Transp. Policy 12 (2), 137–151. https://doi.org/10.1016/J.TRANPOL.2005.01.001.
Taplin, I.M., 2006. Restructuring and reconfiguration: the EU textile and clothing industry adapts to change. Eur. Bus. Rev. 18 (3), 172–186. https://doi.org/10.1108/09555340610663719.
Timmer, M.P., Dietzenbacher, E., Los, B., Stehrer, R., de Vries, G.J., 2015. An Illustrated User Guide to the World Input–Output Database: the Case of Global Automotive Production. Rev. Int. Econ. 23 (3), 575–605. https://doi.org/10.1111/ROIE.12178.
To, W.M., Lee, P.K.C., 2018. GHG emissions from China's international sea freight transport: a review and the future trend. International Journal of Shipping and Transport Logistics 10 (4), 455. https://doi.org/10.1504/IJSTL.2018.093483.
Trotta, G., 2019. Assessing energy efficiency improvements, energy dependence, and CO2 emissions in the European Union using a decomposition method. Energ. Effic. 12 (7), 1873–1890. https://doi.org/10.1007/S12053-019-09818-7.
Tsai, W.-T., 2021. Trend analysis of Taiwan's greenhouse gas emissions from the energy sector and its mitigation strategies and promotion actions. Atmosphere 12 (7), 859. https://doi.org/10.3390/atmos12070859.
Tukker, A., Dietzenbacher, E., 2013. Global multiregional input–output FRAMEWORKS: an introduction and outlook. Econ. Syst. Res. 25 (1), 1–19. https://doi.org/10.1080/09535314.2012.761179.
Tutak, M., Brodny, J., 2022. Renewable energy consumption in economic sectors in the EU-27. The impact on economics, environment and conventional energy sources. A 20-year perspective. J. Clean. Prod. 345, 131076. https://doi.org/10.1016/J.JCLEPRO.2022.131076.
UNEP (United Nations Environmental Program), 2011. Decoupling: natural resource use and environmental impacts from economic growth. Retrieved August 20, 2024, from. https://www.unep.org/resources/report/decoupling-natural-resource-use-and-environmental-impacts-economic-growth.
United Nations, 2023. Facts and figures. https://www.un.org/en/actnow/facts-and-figures.
Valodka, I., Snieska, V., 2020. International trade impact on global warmth in textile and clothing industry. *Rural development 2019, 2019*(1), 502–507. Doi:10.15544/RD.2019.049.
Valodka, I., Snieška, V., Mihi-Ramirez, A., 2020. Impact of the international trade on the EU clothing industry carbon emissions. Eng. Econ. 31 (3), 314–322. https://doi.org/10.5755/j01.ee.31.3.25012.
Wang, Q., Su, M., 2020. Drivers of decoupling economic growth from carbon emission – an empirical analysis of 192 countries using decoupling model and decomposition method. Environ. Impact Assess. Rev. 81, 106356. https://doi.org/10.1016/J.EIAR.2019.106356.
Wang, Q., Zhao, M., Li, R., 2019. Decoupling sectoral economic output from carbon emissions on city level: a comparative study of Beijing and Shanghai, China. J. Clean. Prod. 209, 126–133. https://doi.org/10.1016/j.jclepro.2018.10.188.
Wang, Q., Wang, L., Li, R., 2024. Trade openness helps move towards carbon neutrality—insight from 114 countries. Sustain. Dev. 32 (1), 1081–1095. https://doi.org/10.1002/SD.2720.

Wei, L., Jiang, X., Yan, H., Lenzen, M., Li, M., Malik, A., Reiner, V., Wang, Z., Hong, S., 2024. Outsourcing carbon emissions of the expanding affluent groups in China. Environ. Impact Assess. Rev. 106, 107541. https://doi.org/10.1016/J.EIAR.2024.107541.
Wicki, L., Wicka, A., 2022. Is the EU agriculture becoming low-carbon? Trends in the intensity of GHG emissions from agricultural production. ECONOMIC SCIENCE FOR RURAL DEVELOPMENT 56, 68–78. https://doi.org/10.22616/ESRD.2022.56.007.
Wiebe, K.S., 2018. Identifying emission hotspots for low carbon technology transfers. J. Clean. Prod. 194, 243–252. https://doi.org/10.1016/j.jclepro.2018.05.003.
Wiedmann, T., 2009. Editorial: carbon footprint and input–output analysis – an introduction. Econ. Syst. Res. 21 (3), 175–186. https://doi.org/10.1080/09535310903541256.
Wiedmann, T., Minx, J.C., 2008. A definition of 'carbon footprint'. In: In: C. C. Pertsova, Ecological Economics Research Trends: Chapter 1. Nova Science Publishers, Hauppauge NY, USA, pp. 1–11. https://www.researchgate.net/publication/247152314_A_Definition_of_Carbon_Footprint.
Wong, M.C., Au, K.F., 2007. Central and eastern European countries and North Africa: the emerging clothing supplying countries to the EU. J. Fash. Mark. Manag. 11 (1), 56–68. https://doi.org/10.1108/13612020710734409.
World Bank, 2024. World development indicators. https://data.worldbank.org/.
Wu, Y., Zhu, Q., Zhu, B., 2018. Decoupling analysis of world economic growth and CO2 emissions: a study comparing developed and developing countries. J. Clean. Prod. 190, 94–103. https://doi.org/10.1016/j.jclepro.2018.04.139.
Wu, Z., Zhao, M., Ye, Q., 2023. The influence of technology improvements and the consistency of environmental and economic indicators on decoupling of greenhouse gas emissions and economic growth. Sustainable Production and Consumption 42, 14–22. https://doi.org/10.1016/j.spc.2023.09.003.
Yuan, R., Rodrigues, J.F.D., Tukker, A., Behrens, P., 2022a. The statistical projection of global GHG emissions from a consumption perspective. Sustainable Production and Consumption 34, 318–329. https://doi.org/10.1016/J.SPC.2022.09.021.
Yuan, R., Rodrigues, J.F.D., Wang, J., Tukker, A., Behrens, P., 2022b. A global overview of developments of urban and rural household GHG footprints from 2005 to 2015. Sci. Total Environ. 806, 150695. https://doi.org/10.1016/j.scitotenv.2021.150695.
Zhang, J., Han, M., 2022. Production- and consumption-based carbon emission decoupling and decomposition of the belt and road countries. Front. Environ. Sci. 10, 981785. https://doi.org/10.3389/fenvs.2022.981785.
Zhao, L., Kim, K., 2021. Responding to the COVID-19 pandemic: practices and strategies of the global clothing and textile value chain. Cloth. Text. Res. J. 39 (2), 157–172. https://doi.org/10.1177/0887302X21994207.
Zhao, M., Zhou, Y., Meng, J., Zheng, H., Cai, Y., Shan, Y., Guan, D., Yang, Z., 2021. Virtual carbon and water flows embodied in global fashion trade - a case study of denim products. J. Clean. Prod. 303, 127080. https://doi.org/10.1016/j.jclepro.2021.127080.
Zor, S., 2023. Conservation or revolution? The sustainable transition of textile and apparel firms under the environmental regulation: evidence from China. J. Clean. Prod. 382, 135339. https://doi.org/10.1016/j.jclepro.2022.135339.