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# Carbon Footprint Embodied in Global Fiber Trades

Ihlas Sovbetov

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## ABSTRACT

This study offers a novel approach to analyzing environmental degradation in the context of international trade by applying an Environmental Gravity Model. Covering 166 countries over the period 2000 to 2022, the study examines the carbon footprint embodied in global fiber trade, focusing on the effects of trade value, trade weight, and trade distance on emissions. The findings reveal that synthetic fibers – such as polyester, acrylic, and polyamide – impose significantly higher environmental burdens due to their energy-intensive production processes and heightened sensitivity to trade-related factors. In contrast, natural fibers, including bamboo and hemp, exhibit lower embodied carbon footprints, although cotton, wool, and silk display notable emissions linked to production and long-distance transportation. The study highlights the need for targeted policy interventions to promote low-carbon technologies, optimize trade logistics, and encourage the use of sustainable natural fibers.

## 摘要

本研究通过应用环境重力模型，为分析国际贸易背景下的环境退化提供了一种新方法。该研究涵盖了2000年至2022年期间的166个国家，考察了全球纤维贸易中体现的碳足迹，重点关注贸易价值、贸易权重和贸易距离对排放的影响。研究表明，合成纤维，如聚酯、丙烯酸和聚酰胺，由于其能源密集型的生产过程和对贸易相关因素的高度敏感性，对环境造成了更大的负担。相比之下，包括竹子和大麻在内的天然纤维表现出较低的隐含碳足迹，尽管棉花、羊毛和丝绸显示出与生产和长途运输相关的显著排放。该研究强调，需要有针对性的政策干预，以促进低碳技术，优化贸易物流，并鼓励使用可持续的天然纤维。

## KEYWORDS

Carbon footprint; environmental gravity model; sustainable fiber trade; economics; natural fibers; trade distance

## 关键词

碳足迹; 环境重力模型; 可持续纤维贸易; 经济学; 天然纤维; 贸易距离

## JEL CODE

F18; Q56; R41

## Introduction

The carbon footprint embodied in global fiber trade is a critical area of study due to the textile industry's substantial contribution to greenhouse gas (GHG) emissions and environmental degradation (Niinimäki et al. 2020). The industry, responsible for 8–10% of global carbon emissions – more than the aviation and shipping sectors combined – has drawn significant attention as a major target for carbon reduction efforts (Bailey, Basu, and Sharma 2022).

Fiber production plays a pivotal role in the textile industry's environmental footprint. Synthetic fibers dominate the global market, accounting for 67% of total fiber production in 2023, with polyester alone comprising 57% (Textile Exchange 2024). This trend is projected to grow, driven by increasing global fiber consumption and population growth. However, synthetic fibers pose significant environmental challenges. Polyester production, for instance, emitted over 706 million tons of GHGs in 2015, equivalent to the annual emissions of 185 coal-fired power plants (Kirchain et al. 2015). Additionally, synthetic fibers decompose extremely slowly – taking 20 to over 200 years – and contribute to microplastic pollution, with up to 700,000 microplastic fibers released per laundry cycle filled with synthetic garments (Sajn 2019).

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In contrast, natural fibers such as cotton, wool, hemp, and silk offer more environmentally friendly alternative. Derived from renewable sources, natural fibers are biodegradable, decompose within weeks, and require less energy and water during production. For instance, cotton decomposes within 1–2 weeks compared to over 200 years for polyester (Baloyi et al. 2024). Additionally, natural fibers shed biodegradable particles during laundering, reducing their environmental impact on ecosystems. These characteristics highlight the potential role of natural fibers in mitigating the textile industry's carbon footprint.

The global trade of fibers further exacerbates these challenges. Emissions embedded in international trade, which account for 20–30% of global carbon emissions (Wiedmann and Lenzen 2018), are a critical concern. The transportation of raw materials, intermediates, and finished fiber products across geographically dispersed and long-distance supply chains significantly increases carbon emissions, particularly as freight transport remains heavily dependent on fossil fuels. Furthermore, the fragmentation of production processes across multiple countries intensifies the environmental impact of fiber trade, necessitating a closer examination of emissions at each stage of the supply chain.

Despite these pressing issues, the existing literature has not thoroughly explored the carbon footprint of the global trade in fibers, particularly regarding emissions embedded across the entire supply chain – from production to transportation and consumption. Previous studies (Golgeci, Makhmadshoev, and Demirbag 2021; Groetsch 2024; Harris et al. 2020; Khan et al. 2020; Lu et al. 2020; Ozdemir 2024; Rahaman, Pranta, and Repon 2024; Wang, Xiong, and Ma 2022; Xiong and Wu 2021; Xu et al. 2021; Zheng 2021) have primarily focused on the environmental impacts of specific fiber types or isolated production stages. These studies often examine single countries or, at most, a small number of developed countries, limiting their ability to capture the broader patterns and complexities of global fiber trade. Moreover, they typically rely on traditional environmental degradation models – such as the Environmental Kuznets Curve (EKC), IPAT, and STIRPAT frameworks – which do not explicitly account for geographical distance or trade volume, both of which play a significant role in transportation-related carbon emissions.

To address these gaps, this study makes three key contributions. First, it proposes a novel Environmental Gravity Model (EGM), which explicitly incorporates trade value, trade weight, and travel distance as determinants of embodied carbon emissions in international fiber trade. This spatially explicit and trade-specific approach provides a more nuanced understanding of how international trade contributes to environmental degradation. Second, the study offers a comprehensive empirical analysis covering 166 countries, which, to the best of our knowledge, represents the largest dataset employed to examine the embodied carbon footprint in global fiber trade to date. Third, the study provides new insights using recent data spanning from 2000 to 2022, allowing for a contemporary analysis that reflects current trade patterns and environmental challenges.

Our approach contrasts with traditional models of environmental degradation, such as the Environmental Kuznets Curve (EKC), IPAT, STIRPAT, and DPSIR frameworks. While these models offer valuable macro-level insights into the relationship between economic development and environmental impact, they often overlook the direct role of international trade and its logistical complexities. For example, the EKC typically focuses on national economic indicators, such as GDP and GDP squared, without accounting for the carbon emissions directly associated with trade flows and transport distance. Similarly, IPAT and STIRPAT emphasize population, affluence, and technology, but do not incorporate spatial factors like cradle-to-gate distance or trade weight. By contrast, the EGM applied in this study integrates these trade-specific variables – trade value, trade weight, and distance – providing a more detailed and spatially explicit analysis of carbon emissions embodied in global fiber trade. This methodological advancement allows for more targeted policy recommendations aimed at reducing the environmental impact of international trade.

The findings of the study reveal that synthetic fibers, due to their inherently high production-related emissions and greater sensitivity to trade-related factors, impose a disproportionately larger environmental burden compared to natural fibers. Synthetic fibers such as polyester, acrylic, and polyamide generate significant emissions during production and are particularly sensitive to variations

in trade distance and volume. Conversely, while natural fibers such as bamboo and hemp demonstrate comparatively lower carbon footprints, other natural fibers like cotton, wool, and silk exhibit notable emissions linked to both production processes and long-distance transport requirements.

The study offers several actionable insights for policymakers and industry stakeholders seeking to mitigate the environmental impact of fiber trade. It highlights the need to promote low-carbon production technologies, optimize transport logistics, develop carbon-optimized green trade corridors and encourage the use of sustainable natural fibers. Practical measures include the development of regional supply chains to reduce cross-border transportation distances and the promotion of maritime transport as a lower-emission alternative to air freight. By integrating these strategies, stakeholders can reduce the carbon footprint of global fiber trade and contribute to broader sustainability goals.

By adopting this framework, this study contributes to the growing body of literature on the environmental implications of international trade. Specifically, it bridges the gap between environmental impact analysis and trade logistics modeling, offering a robust, spatially explicit approach to analyzing carbon emissions embodied in global fiber trade. The insights derived from this research are intended to inform future academic inquiry, guide evidence-based policy development, and support the transition toward a more sustainable and low-carbon global textile industry.

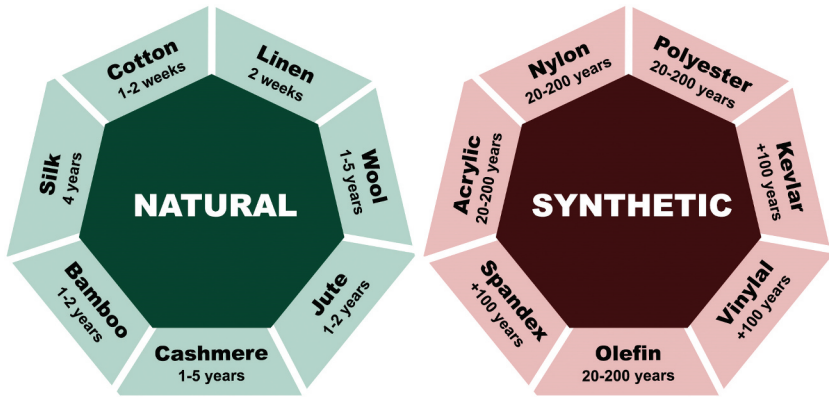
**Carbon footprint in fiber production**

The carbon footprint of textile fibers varies significantly based on their origin, production processes, and environmental impact. Broadly, these fibers can be categorized into natural and synthetic types, each with distinct ecological footprints.

**Natural fibers**

Natural fibers, derived from renewable sources such as plants and animals, are often regarded as more sustainable alternatives to synthetic fibers. However, their production is not without environmental consequences. Natural fibers generally decompose much faster than synthetic fibers (see [Figure 1](#)), taking anywhere from a few weeks to a few years to break down fully.

Cotton, one of the most widely used natural fibers, is celebrated for its biodegradability and comfort. It decomposes in 1–2 weeks, making it one of the fastest-decomposing fibers. However, its cultivation is resource-intensive. For example, producing one kilogram of cotton fabric emits approximately 22 kilograms of CO<sub>2</sub> equivalents and requires an average of 10,000 liters of water (Chapagain, Mathews, and Zhang 2017). The application of pesticides and fertilizers contributes to significant soil and water pollution, negating the carbon sequestration



**Figure 1.** Decomposition duration of natural and synthetic fibres. Source: Green-Tailor.com.<sup>1</sup>

benefits of cotton plants during their growth. Despite its relatively lower greenhouse gas emissions compared to synthetic fibers, cotton’s water consumption is a major concern, as the production of a single cotton shirt demands about 2,700 liters of water (Woensel and Lipp 2020). Organic and recycled cotton offer more sustainable alternatives, mitigating water waste by 99%; however, only 32% of global cotton production was organic or recycled in 2022 (Textile Exchange 2024).

Linen, derived from flax, is another natural fiber that stands out for its low water and energy requirements. Unlike cotton, flax cultivation typically relies on rainwater and requires minimal irrigation or pesticide use. Producing one kilogram of linen fabric generates approximately 25 kilograms of CO<sub>2</sub> equivalents (see Figure 2), making it one of the more eco-friendly natural fibers. Linen decomposes in about two weeks, and its biodegradability, coupled with the use of all parts of the flax plant, reduces waste.

Silk, a luxurious natural fiber of animal origin, is derived from silkworm cocoons. Its production, however, involves significant ethical and environmental considerations. The process of harvesting silk involves killing silkworms, and its cultivation is resource-intensive, relying on fertilizers and pesticides. Producing one kilogram of silk fabric emits approximately 14.9 kilograms of CO<sub>2</sub> equivalents (see Figure 2). Although silk biodegrades in about four years, its environmental benefits are offset by the pollutants generated during production.

Hemp is a low-impact natural fiber similar to flax, requiring little water and no irrigation. It decomposes within a month and emits approximately 16.5 kilograms of CO<sub>2</sub> equivalents per kilogram of production (see Figure 2). Its biodegradability and minimal pesticide use make it a favorable option in sustainable textile production.

Wool, derived from sheep, is another commonly used natural fiber. While it is biodegradable and renewable, decomposing in 1–5 years, its production has a disproportionately high carbon footprint (see Figure 1). Methane emissions from sheep, coupled with the energy-intensive processes involved in shearing and processing, result in emissions of approximately 19 kilograms of CO<sub>2</sub> equivalents per kilogram of wool (see Figure 2).

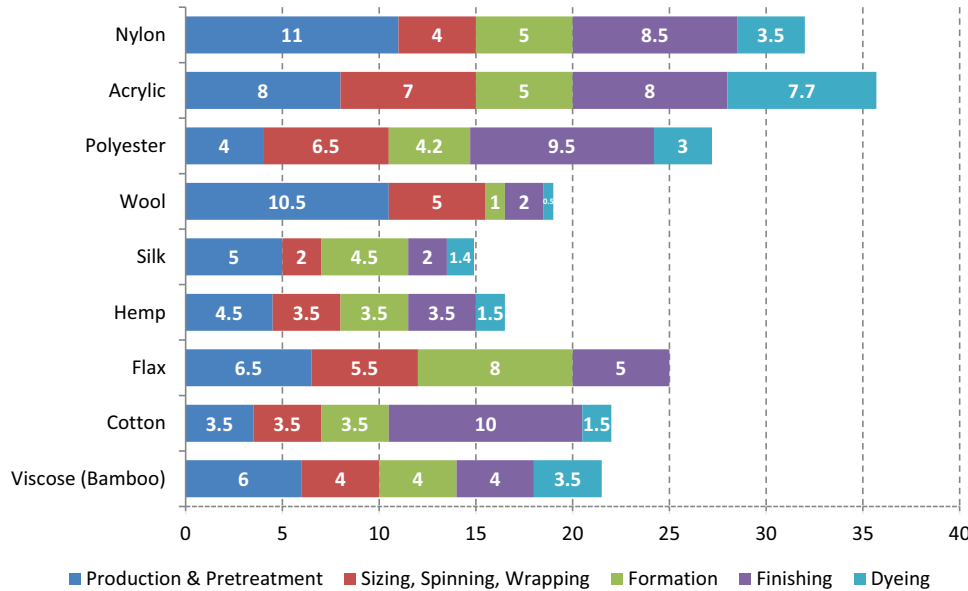


Figure 2. Carbon footprint expressed in kg CO<sub>2</sub> equivalent per kg fiber. Source: Beton et al. (2014).

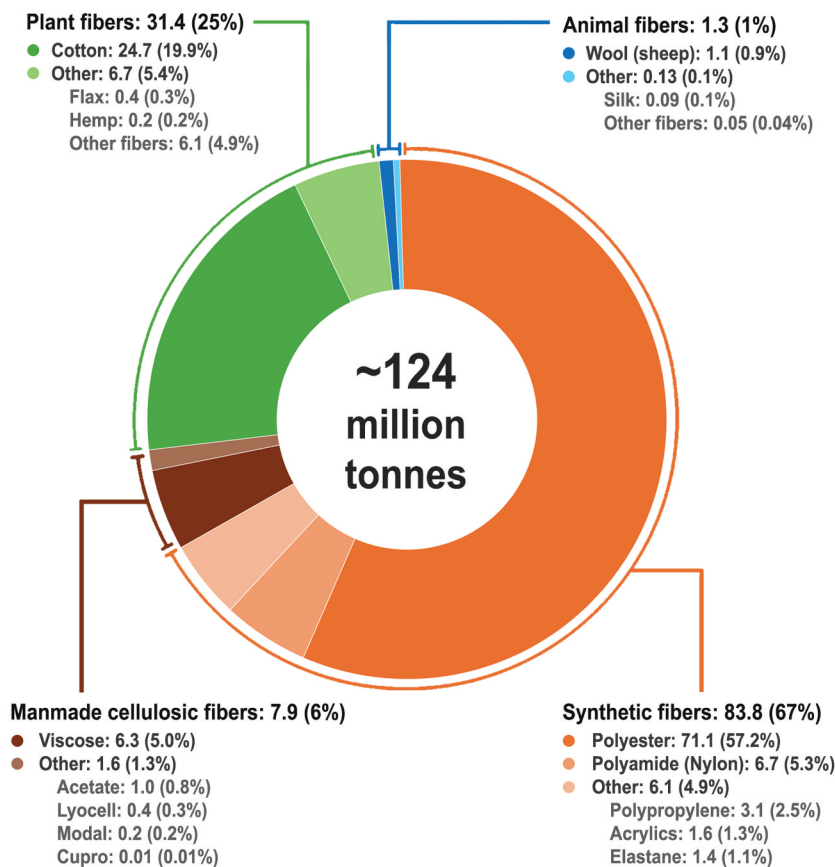
## Synthetic fibers

Synthetic fibers, produced from petrochemicals, dominate the global textile industry, accounting for 67% of total fiber production in 2023 (see [Figure 3](#)). Synthetic fibers are non-biodegradable and can take hundreds of years to decompose (see [Figure 1](#)), posing significant environmental challenges.

Polyester, the most prevalent synthetic fiber, represents 57% of global fiber output (Textile Exchange 2024). Its production emits approximately 27.2 kilograms of CO<sub>2</sub> equivalents per kilogram (see [Figure 2](#)), a relatively low figure compared to some natural fibers. However, polyester's reliance on fossil fuels, non-biodegradability, and the release of microplastics during washing present significant environmental challenges. Each wash can release up to 700,000 microplastic fibers, contributing to marine pollution (Sajn 2019). Polyester takes 200 years or more to decompose, significantly impacting landfill waste (see [Figure 1](#)).

Acrylic, another synthetic fiber, mimics the softness of wool but has a higher carbon footprint. Producing one kilogram of acrylic generates 35.7 kilograms of CO<sub>2</sub> equivalents (see [Figure 2](#)). Like polyester, acrylic is non-biodegradable, takes 200 years to decompose (see [Figure 1](#)), and releases microplastics during washing. Its limited durability further exacerbates its environmental impact, as garments made from acrylic often have a short lifespan.

Nylon, widely used for its strength and elasticity, is another synthetic fiber with significant environmental repercussions. Its production emits approximately 32 kilograms of CO<sub>2</sub> equivalents per kilogram (see [Figure 2](#)), and the process releases nitrous oxide, a greenhouse gas 310 times more



**Figure 3.** Market share of fibers in 2023. Source: Textile Exchange (2024).

potent than CO<sub>2</sub>. Furthermore, the energy-intensive production process of nylon often relies on fossil fuels, contributing to resource depletion and global warming. Like polyester and acrylic, nylon takes around 200 years to decompose (see [Figure 1](#)), making it a long-lasting pollutant in landfills. Like polyester and acrylic, nylon takes around 200 years to decompose (see [Figure 1](#)), making it a long-lasting pollutant in landfills.

### Environmental implications

The environmental impact of textile fibers extends beyond their production phase. Approximately 60% of clothing is discarded within a year of production, often ending up in landfills or incinerators. Additionally, 10–20% of fabric is wasted during garment production, contributing to further environmental degradation. The textile industry is responsible for 10% of global carbon emissions and 20% of clean water pollution, underscoring the need for more sustainable practices ([Igini 2023](#)).

Natural fibers, with their biodegradability and renewable origins, present an opportunity to reduce the textile industry’s carbon footprint. However, their production must be carefully managed to mitigate resource consumption and pollution. Synthetic fibers, on the other hand, require systemic changes in production, usage, and disposal practices to address their environmental challenges. Transitioning to recycled or bio-based alternatives and improving waste management systems are critical steps toward reducing the industry’s ecological impact.

### Carbon footprint embodied in international trade on fibers in 2022

The term “*embodied carbon footprint*” refers to cradle-to-gate greenhouse gas (GHG) emissions, expressed as carbon dioxide equivalents (CO<sub>2</sub>e). It includes all emissions generated from raw material extraction and fiber manufacturing to transportation between trading countries. Transportation emissions are modeled based on the linear distance between the capital cities of the exporting and importing countries, serving as a proxy for the international transport leg of the supply chain.

The cradle-to-gate carbon footprint associated with the international trade of fibers provides valuable insights into the environmental impact of global supply chains. [Table 1](#) presents the trade metrics of fibers in 2022, revealing that the total carbon footprint embodied in the international trade of fibers reached approximately 355.98 million tons of CO<sub>2</sub>. Synthetic fibers, including polyester, acrylic, and polyamide (nylon), accounted for 83% of this total, contributing 297 million tons CO<sub>2</sub>. Conversely, natural fibers such as cotton, flax, and jute collectively accounted for 58.11 million tons CO<sub>2</sub>, representing 17% of the total fiber CO<sub>2</sub> emissions. This disparity underscores the significant environmental burden associated with synthetic fiber production and transportation.

**Table 1.** Trade metric of fibers in 2022.

| Fiber             | Carbon Footprint (K tons CO <sub>2</sub> ) | Trade Value (Million USD) | Trade Weight (K tons) | Trade Travel Distance (Km) | Embodied CO <sub>2</sub> per Trade Value | Embodied CO <sub>2</sub> per Trade Weight | Embodied CO <sub>2</sub> per Trade Distance |
|-------------------|--------------------------------------------|---------------------------|-----------------------|----------------------------|------------------------------------------|-------------------------------------------|---------------------------------------------|
| Bamboo            | 28.00                                      | 210.23                    | 236.02                | 114,548.20                 | 0.13                                     | 0.12                                      | 0.24                                        |
| Coir              | 36.34                                      | 15.10                     | 7.74                  | 116,736.46                 | 2.41                                     | 4.70                                      | 0.31                                        |
| Cotton            | 53,294.41                                  | 40,671.21                 | 13,975.04             | 446,456.64                 | 1.31                                     | 3.81                                      | 119.37                                      |
| Flax              | 1,340.72                                   | 1,800.69                  | 608.78                | 380,790.55                 | 0.74                                     | 2.20                                      | 3.52                                        |
| Hemp              | 132.17                                     | 79.24                     | 41.16                 | 375,187.76                 | 1.67                                     | 3.21                                      | 0.35                                        |
| Jute              | 713.69                                     | 296.05                    | 289.31                | 241,893.46                 | 2.41                                     | 2.47                                      | 2.95                                        |
| Silk              | 63.01                                      | 932.60                    | 23.82                 | 173,103.45                 | 0.07                                     | 2.65                                      | 0.36                                        |
| Wool              | 2,501.53                                   | 9,322.72                  | 1,002.99              | 132,854.33                 | 0.27                                     | 2.49                                      | 18.83                                       |
| Polyester         | 252,860.00                                 | 1,142.25                  | 63,000.00             | 982,558.00                 | 221.38                                   | 4.01                                      | 256.31                                      |
| Acrylic           | 7,248.00                                   | 21,000.00                 | 1,600.00              | 345,144.00                 | 0.35                                     | 4.53                                      | 21.00                                       |
| Polyamide (Nylon) | 37,765.00                                  | 13,900.00                 | 6,500.00              | 392,773.00                 | 2.72                                     | 5.81                                      | 96.15                                       |

Source: Chatham House (2024), Textile Exchange (2024).

The carbon efficiency metrics reveal notable differences between fiber types. Polyester has the highest carbon intensity per trade value, with 221.37 kg CO<sub>2</sub> per USD, reflecting its substantial emissions relative to its low trade value. In contrast, natural fibers exhibit more favorable metrics, with an average of 1.01 kg CO<sub>2</sub> per USD. However, jute and coir stand out with higher values of 2.41 kg CO<sub>2</sub> per USD, indicating relatively less efficient carbon profile in economic terms.

In terms of emissions per trade weight, synthetic fibers again show elevated values. Polyamide (nylon) has the highest emissions per unit weight, at 5.81 kg CO<sub>2</sub> per traded kilogram, followed by acrylic at 4.53 kg. Natural fibers performed better overall, with an average of 1.19 kg CO<sub>2</sub> per traded kilogram, though cotton, the most widely traded natural fiber by weight, has a relatively higher intensity of 3.81 kg CO<sub>2</sub> per traded kilogram.

When considering emissions per trade distance, polyester is the most impactful, with 256.31 tons of CO<sub>2</sub> per km. Among natural fibers, cotton leads in emissions per distance at 119.37 tons of CO<sub>2</sub>, influenced by its significant trade volume and long-distance transportation involved in its global supply chain.

A comparative analysis of fiber types further highlights these disparities in carbon footprints. Among natural fibers, cotton trade dominated the carbon footprint, contributing 53,294 K tons CO<sub>2</sub>, equivalent to 91.7% of emissions in this category. Cotton's extensive global demand largely explains its significant environmental impact. In contrast, other natural fibers, such as flax and jute, exhibited relatively lower carbon footprints but varied in efficiency depending on trade weight and distance.

For synthetic fibers, polyester accounted for 72% of emissions in this category, driven by its high production volume and substantial trade distances. Acrylic and polyamide also demonstrated significant environmental burdens, highlighting the resource-intensive nature of synthetic fiber production.

Specialized fibers like silk and bamboo displayed unique carbon efficiency profiles, despite their smaller trade volumes. Bamboo had a balanced carbon footprint with emissions of 0.12 K tons CO<sub>2</sub> per trade weight, whereas silk, despite its high unit value, exhibited a moderate carbon intensity of 2.65 K tons CO<sub>2</sub> per trade weight.

Addressing the environmental inefficiencies of synthetic fibers, particularly polyester, acrylic, and polyamide, is crucial. Transitioning to sustainable production technologies, optimizing supply chains, and reducing transportation distances can significantly lower their carbon footprint. Promoting natural fibers with lower carbon intensities, supported by sustainable farming and processing, provides an additional pathway to mitigating environmental impacts. These measures are essential for fostering sustainable international fiber trade and reducing the ecological burden of global supply chains, emphasizing the urgent need for coordinated efforts to achieve long-term sustainability in the fiber industry.

## Data & methodology

### Methodology

The gravity model in economics serves as a theoretical framework for analyzing and predicting trade flows between countries or regions. Analogous to Newton's law of gravitation, it postulates that economic interactions are directly proportional to the economic mass of the trading partners and inversely proportional to the distance between them. The basic form of the gravity model is expressed as:

$$F_{ij} = G \cdot \frac{(M_i M_j)}{D_{ij}^\beta} \quad (1)$$

where  $F_{ij}$  represents the trade flow between countries  $i$  and  $j$ ,  $M_i$  and  $M_j$  denote the economic “mass” of countries  $i$  and  $j$ , respectively (GDP, population), and  $D_{ij}$  is the geographical distance between the two countries. The  $G$  is a constant of proportionality, and  $\beta$  captures the elasticity of trade flows with respect to distance.

For empirical estimation, the gravity model is typically log-linearized to facilitate interpretation and estimation:

$$\ln(F)_{ij} = \ln(G) + \alpha_1 \ln(M)_i + \alpha_2 \ln(M)_j - \beta \ln(D)_{ij} + \varepsilon_{ijt} \quad (2)$$

The model assumes a positive relationship between economic mass and trade flows, while the relationship between distance and trade is typically negative due to transportation costs and other frictions.

This study adopts a novel approach by applying the gravity model framework to analyze environmental degradation in the context of international trade. Specifically, the model examines the carbon footprint embodied in fiber trade flows, hypothesizing that environmental degradation – measured via embodied carbon emissions – is positively associated with trade distance. Unlike traditional gravity models, where distance typically acts as a barrier to trade volume, this adaptation recognizes that longer trade distances exacerbate transportation-related emissions, thereby intensifying environmental impact through increased fuel consumption and related carbon emissions.

Accordingly, the cross-sectional Environmental Gravity (EG) model is specified as:

$$\Delta \ln(CO_{ijt}) = \alpha_{ij} + \phi_{1j} \Delta \ln(TV_{ijt}) + \phi_{2j} \Delta \ln(TW_{ijt}) + \phi_{3j} \Delta \ln(TD_{ijt}) + \gamma_{ij} + \lambda_{tj} + \varepsilon_{ijt} \quad (3)$$

where  $\Delta \ln(CO_{ijt})$  denotes the change in the natural logarithm of the carbon footprint associated with fiber  $j$  exported from country  $i$  at time  $t$ ;  $\Delta \ln(TV_{ijt})$  is the change in trade value;  $\Delta \ln(TW_{ijt})$  is the change in trade weight;  $\Delta \ln(TD_{ijt})$  represents the change in linear capital-to-capital distances.<sup>2</sup> The error term  $\varepsilon_{ijt}$  is assumed to be white noise and stationary. The  $\alpha_{ij}$  captures baseline carbon emissions not explained by trade factors, reflecting cradle-to-gate emission differences across fiber types. The  $\gamma_{ij}$  represents country-specific fixed effects for fiber  $j$ , accounting for unobserved heterogeneity that doesn't vary over time, whereas  $\lambda_{tj}$  is time-specific fixed effects for fiber  $j$ , capturing year-to-year shocks or global trends for fiber  $j$ .

In this framework, the coefficients  $\phi_1$ ,  $\phi_2$ , and  $\phi_3$  measure the elasticity of carbon emissions with respect to trade value, trade weight, and trade distance, respectively. The  $\phi_1$  captures the influence of trade value on emissions, while  $\phi_2$  assesses the impact of trade weight, recognizing that heavier shipments generally increase transport-related emissions. The  $\phi_3$  quantifies the effect of distance, emphasizing that longer transportation routes significantly amplify a fiber's embedded carbon footprint.

In contrast to traditional environmental degradation models – such as the Environmental Kuznets Curve (EKC), IPAT, STIRPAT, and DPSIR frameworks – this study's Environmental Gravity Model (EGM) offers a more targeted, trade-specific analysis of carbon emissions. While the EKC hypothesizes an inverted-U relationship between economic growth and environmental degradation, typically using GDP and GDP squared as explanatory variables, it often omits the spatial and logistical complexities of international trade. Similarly, the IPAT and STIRPAT models, though useful in capturing broad relationships between population, affluence, technology, and environmental impact, do not explicitly account for trade flows, geographical distance, or transportation logistics that are pivotal in determining emissions in global trade networks. DPSIR, while providing a comprehensive causal framework for environmental policy, lacks quantitative rigor in modeling emissions directly linked to trade patterns.

By contrast, the EGM integrates trade value, trade weight, and geographical distance – variables that are direct drivers of carbon emissions in fiber trade. Additionally, the inclusion of spatial factors, particularly trade distance, allows for a more granular and empirically grounded assessment of

transportation-related emissions. This modeling approach facilitates a deeper understanding of the environmental consequences of global fiber trade and yields more actionable policy insights aimed at mitigating the carbon footprint embedded in international supply chains.

For robustness, we extend the baseline model by incorporating a binary dummy variable (NDUM), which distinguishes between natural and synthetic fibers. NDUM equals 1 for natural fibers and 0 for synthetic fibers. This specification allows us to evaluate whether fiber type systematically influences the carbon footprint beyond the effects of trade value, weight, and distance. The robustness check is estimated on the combined sample of both natural and synthetic fibers. The augmented model is specified as follows:

$$\Delta \ln(CO_{it}) = \alpha_i + \phi_1 \Delta \ln(TV_{ij}) + \phi_2 \Delta \ln(TW_{it}) + \phi_3 \Delta \ln(TD_{it}) + \phi_4 NDUM_{it} + \gamma_i + \lambda_t + \varepsilon_{it} \quad (4)$$

In this formulation,  $\phi_4$  captures the differential impact of fiber type on the carbon footprint, providing additional insight into whether natural fibers exhibit systematically lower embodied carbon emissions relative to synthetic fibers, controlling for trade factors.

## Data

Data for this analysis are sourced from the Chatham House Resource Trade Database (CHRTD), which documents bilateral trade in natural resources across over 200 countries and territories from 2000 to 2022. The database includes comprehensive data on trade value, weight, and associated carbon footprints for 8 natural fibers, such as bamboo, coir, cotton, flax, hemp, jute, silk, and wool. The database includes comprehensive data on trade value, weight, and associated carbon footprints for 8 natural fibers, such as bamboo, coir, cotton, flax, hemp, jute, silk, and wool. The study also incorporates trade data for 3 man-made synthetic fibers – polyesters, acrylics, and olefin – sourced from trade map.<sup>3</sup> These synthetic fibers serve as critical indicators for assessing the sustainability and environmental implications of international trade, complementing the analysis of natural fibers.

For example, global cotton trade flows in 2022 reveal the dominance of exports from the United States to China, followed by flows from India to Bangladesh and Vietnam to China. The United States emerged as the largest exporter, with \$10.7 billion in trade, while China led imports with \$8.5 billion. Notable growth occurred in Brazil's exports to China and Pakistan, increasing by 64% and 61%, respectively. Conversely, trade flows such as Hong Kong to China and Australia to China experienced declines of over 30%, reflecting shifting trade patterns. Similar patterns are observed in the silk trade, where China remains the leading exporter, followed by Vietnam and Romania. While China to Malaysia and China to Madagascar trade flows decreased significantly, countries like North Korea and Myanmar showed substantial growth in silk exports.

The right-hand side of the [Figure 4](#) shows global silk trade where China remained the leading exporter, generating \$474 million, with Vietnam and Romania following. Major trade flows included exports from China to India and Vietnam to India, while China to Malaysia and China to Madagascar experienced steep declines of over 30%. North Korea and Myanmar demonstrated significant growth in silk exports, with increases of 125% and 111%, respectively, while Malaysia and Germany saw declines. India led silk imports, followed by Italy and Romania, with rapid growth observed in Slovenia and Tunisia, while Malaysia and Madagascar showed substantial reductions. These trends highlight both the traditional dominance of China in silk trade and emerging shifts in trade routes.

## Results

### Preliminary checks

The study employs panel ordinary least squares (OLS) estimation for the EG model. The OLS required all input data to be stationary at level, thus the study confirms stationarity of the series via the augmented Dickey-Fuller test, reported at [Table 2](#).

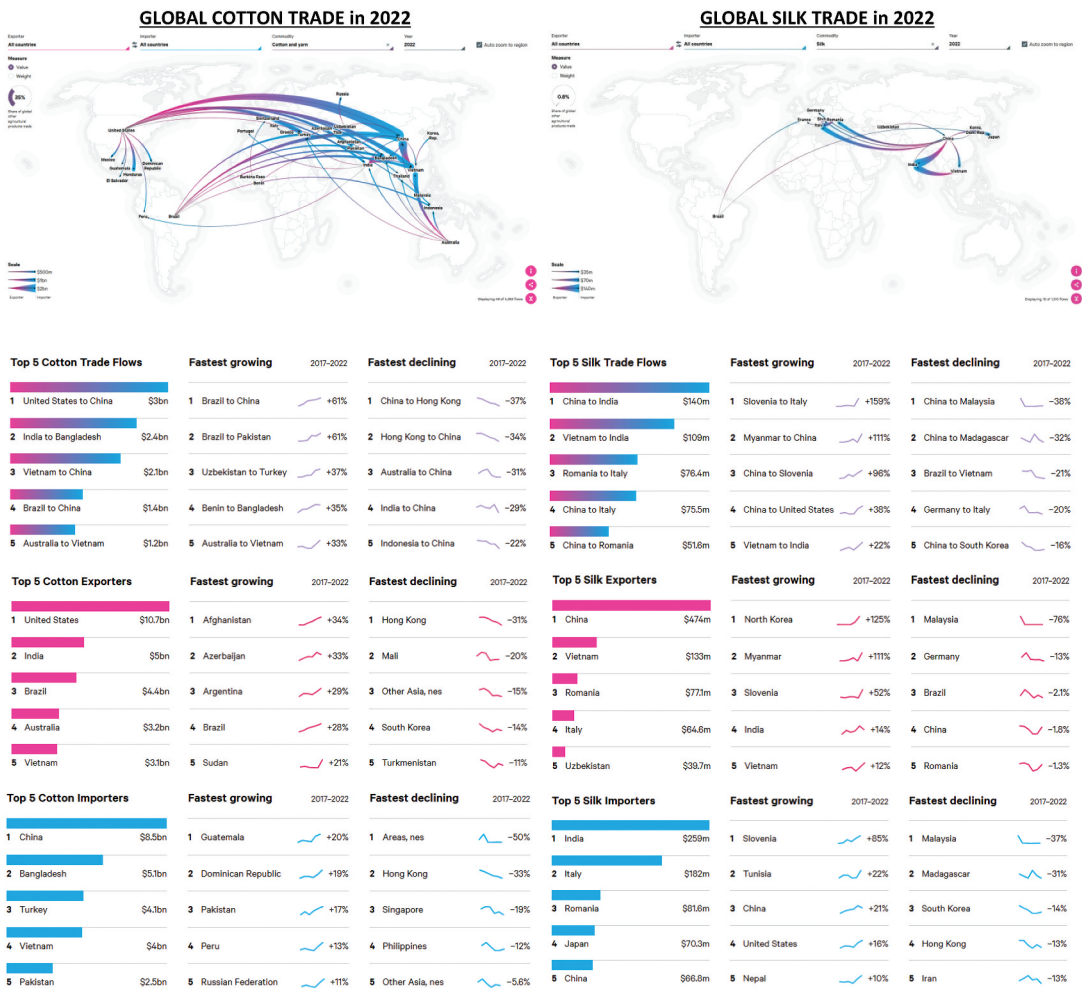


Figure 4. Global trade flows of cotton and silk in 2022. Source: Chatham House (2024).

### Core results

Table 3 presents the results of the EG panel model, which estimates the factors influencing the carbon footprint embodied in fiber trade. The model fits well overall, with adjusted  $R^2$  values ranging from 0.5011 for Jute to 0.6627 for Cotton, indicating that the model explains a substantial proportion of the variation in the carbon footprint across fiber types. Heteroskedasticity and autocorrelation consistent (HAC) robust standard errors are employed to ensure statistical reliability.

The intercept values represent the baseline carbon footprint that is not explained by trade-related factors such as trade value, weight, and distance. These intercepts vary significantly across fibers, reflecting the intrinsic differences in cradle-to-gate emissions. The average intercept value for natural fibers is approximately 0.21, whereas it is significantly higher at around 0.55 for synthetic fibers. This indicates that synthetic fibers have inherently higher cradle-to-gate emissions due to their energy-intensive production processes, particularly for Polyester (0.5121) and Polyamide (0.6748). Among natural fibers, Wool (0.4224) and Silk (0.3201) also show relatively high intercepts, indicating significant emissions during production. In contrast, fibers like Bamboo (0.0524) and Hemp (0.1043) have much lower intercepts, reflecting their comparatively lower production-related carbon footprints.

**Table 2.** Augmented Dickey-Fuller unit root test.

| Fiber             | Type      | Variable         | ADF Chi-square | Cross-section | Observation |
|-------------------|-----------|------------------|----------------|---------------|-------------|
| Bamboo            | Natural   | Carbon Footprint | 144.46***      | 33            | 556         |
|                   |           | Trade Value      | 90.38***       | 33            | 546         |
|                   |           | Trade Weight     | 114.46***      | 33            | 556         |
| Coir              | Natural   | Carbon Footprint | 108.856*       | 46            | 547         |
|                   |           | Trade Value      | 114.23**       | 46            | 548         |
|                   |           | Trade Weight     | 116.44**       | 46            | 548         |
| Cotton            | Natural   | Carbon Footprint | 185.87***      | 52            | 720         |
|                   |           | Trade Value      | 161.43***      | 52            | 725         |
|                   |           | Trade Weight     | 170.90***      | 52            | 719         |
| Flax              | Natural   | Carbon Footprint | 134.94***      | 49            | 734         |
|                   |           | Trade Value      | 150.41***      | 49            | 731         |
| Hemp              | Natural   | Trade Weight     | 154.411***     | 49            | 731         |
|                   |           | Carbon Footprint | 117.26**       | 47            | 565         |
|                   |           | Trade Value      | 118.71**       | 47            | 567         |
| Jute              | Natural   | Trade Weight     | 114.39*        | 47            | 565         |
|                   |           | Carbon Footprint | 503.85***      | 56            | 593         |
|                   |           | Trade Value      | 508.21***      | 56            | 597         |
| Silk              | Natural   | Trade Weight     | 503.85***      | 56            | 593         |
|                   |           | Carbon Footprint | 78.01***       | 29            | 359         |
|                   |           | Trade Value      | 88.99***       | 29            | 364         |
| Wool              | Natural   | Trade Weight     | 76.56**        | 29            | 361         |
|                   |           | Carbon Footprint | 88.41**        | 32            | 425         |
|                   |           | Trade Value      | 116.79***      | 32            | 426         |
| Polyester         | Synthetic | Trade Weight     | 92.15***       | 32            | 425         |
|                   |           | Carbon Footprint | 189.15***      | 48            | 711         |
|                   |           | Trade Value      | 192.36***      | 48            | 708         |
| Acrylic           | Synthetic | Trade Weight     | 187.04***      | 48            | 708         |
|                   |           | Carbon Footprint | 204.41***      | 40            | 527         |
|                   |           | Trade Value      | 200.09***      | 40            | 527         |
| Polyamide (Nylon) | Synthetic | Trade Weight     | 192.47***      | 40            | 527         |
|                   |           | Carbon Footprint | 231.10***      | 41            | 550         |
|                   |           | Trade Value      | 234.76***      | 41            | 550         |

Data series are change in the natural logarithmic form. The ADF statistics are in levels.

**Table 3.** Results of environmental gravity model.

| Fiber                            | TV       | TW        | TD        | Intercept | NDUM      | R <sup>2</sup> | Country | Obs. |
|----------------------------------|----------|-----------|-----------|-----------|-----------|----------------|---------|------|
| <b>Panel A: Natural Fibers</b>   |          |           |           |           |           |                |         |      |
| Bamboo                           | 0.1266** | 0.8539*** | 0.6215**  | 0.0524*   | –         | 0.6316         | 166     | 3818 |
| Coir                             | 0.3119*  | 0.7356*** | 0.7158**  | 0.1307*   | –         | 0.5208         | 166     | 3818 |
| Cotton                           | 0.3208** | 0.8806*** | 0.7439*** | 0.2239**  | –         | 0.6627         | 166     | 3818 |
| Flax                             | 0.2779** | 0.7776*** | 0.6781**  | 0.1739*   | –         | 0.5856         | 166     | 3818 |
| Hemp                             | 0.2792*  | 0.8633*** | 0.7213*** | 0.1043**  | –         | 0.5647         | 166     | 3818 |
| Jute                             | 0.1484*  | 1.0076*** | 0.8649*** | 0.2155**  | –         | 0.5011         | 166     | 3818 |
| Silk                             | 0.1711** | 0.9673*** | 0.7928*** | 0.3201**  | –         | 0.6753         | 166     | 3818 |
| Wool                             | 0.0972*  | 1.0649*** | 0.6410*** | 0.4224*   | –         | 0.5329         | 166     | 3818 |
| <b>Panel B: Synthetic Fibers</b> |          |           |           |           |           |                |         |      |
| Polyester                        | 0.3865** | 1.2785*** | 0.8850**  | 0.5121**  | –         | 0.5437         | 166     | 3818 |
| Acrylic                          | 0.3593** | 1.1574*** | 0.8522*** | 0.4689**  | –         | 0.5718         | 166     | 3818 |
| Polyamide                        | 0.3139*  | 1.1351*** | 0.7083*** | 0.6748**  | –         | 0.5482         | 166     | 3818 |
| <b>Panel C: All Fibers</b>       |          |           |           |           |           |                |         |      |
| All Fibers                       | 0.3019** | 1.1435*** | 0.7903*** | 0.5314**  | –0.2439** | 0.5462         | 166     | 3818 |

Dependent variable is carbon footprint embodied in fiber trade in natural logarithmic form. The model uses heteroskedasticity and autocorrelation consistent (HAC) robust standard errors. Statistical significance levels are \*:  $p < .10$ , \*\*:  $p < .05$ , \*\*\*:  $p < .01$ .

Trade-related factors, particularly trade weight (TW), emerge as the most critical determinants of the carbon footprint across all fiber types. The coefficients for trade weight range from 0.7356 (Coir) to 1.2785 (Polyester) and are statistically significant at the 1% level for all fibers. The average coefficient for trade weight is 0.867 for natural fibers and 1.190 for synthetic fibers, indicating that synthetic fibers exhibit a steeper increase in carbon emissions with added weight. The results emphasize the strong

relationship between the physical mass of traded goods and emissions, particularly for synthetic fibers like Polyester, Acrylic, and Polyamide, which exhibit the highest elasticities with respect to weight. This pattern underscores the significant environmental burden associated with the transport of heavier synthetic fibers.

The trade distance (TD) also plays a substantial role in determining emissions, with coefficients ranging from 0.6215 (Bamboo) to 0.8850 (Polyester). The average trade distance coefficient is 0.724 for natural fibers and 0.815 for synthetic fibers. While synthetic fibers generally benefit from compact and lightweight properties that reduce emissions per unit weight during transport, their global trade volumes and frequent reliance on energy-intensive modes of transport, such as air freight, contribute to higher overall sensitivity to trade distance. Fibers such as Jute (0.8649) and Silk (0.7928) also exhibit notable dependency on trade distance, reflecting the environmental implications of long supply chains often associated with these natural materials.

Trade value (TV) has a smaller but still statistically significant effect on the carbon footprint. The coefficients range from 0.0972 (Wool) to 0.3865 (Polyester), with natural fibers averaging a trade value coefficient of 0.22 and synthetic fibers averaging 0.35. The relatively lower elasticity of emissions with respect to trade value suggests that emissions are more directly linked to physical and logistical factors, such as weight and distance, rather than the monetary value of traded goods. Synthetic fibers, however, exhibit higher trade value coefficients, reflecting their higher economic value relative to natural fibers.

In addition to the baseline models for natural and synthetic fibers, Panel C presents the results of a robustness check conducted on the combined sample of all fibers, incorporating a binary dummy variable (NDUM), which equals 1 for natural fibers and 0 for synthetic fibers. The results show that NDUM has a coefficient of  $-0.2439$ , which is statistically significant at the 5% level. This negative coefficient indicates that, after controlling for trade value, trade weight, and trade distance, natural fibers are associated with systematically lower embodied carbon emissions compared to synthetic fibers. This finding provides robust evidence supporting the sustainability advantages of natural fibers in global trade, independent of other trade-related factors.

These findings collectively highlight the disproportionate environmental burden posed by synthetic fibers due to their high production-related emissions and heightened sensitivity to trade weight and distance. In light of these results, targeted policy interventions are necessary to mitigate emissions and promote more sustainable fiber trade practices. Key recommendations include promoting low-carbon production technologies, particularly for synthetic fibers, enhancing transport logistics, and incentivizing the use of more sustainable natural fibers. Furthermore, improving supply chain efficiency and investing in cleaner transportation methods are critical strategies for reducing the environmental impact of global fiber trade. These insights form the basis for the operational recommendations detailed in the following section, which outlines specific measures aimed at reducing the carbon footprint of long-distance fiber trade.

### ***Policy implications and operational recommendations***

Building on the empirical findings of the environmental gravity model, this section outlines several targeted policy measures designed to mitigate emissions and promote sustainable trade practices in the global fiber industry.

First, promoting maritime transportation wherever feasible can significantly reduce emissions, as sea freight benefits from natural waterway flows and lower fuel consumption per tonne-kilometer compared to air or road transport.

Second, the development and identification of “*green corridors*”—carbon-optimized trade routes designed to minimize transport distances – can further enhance efficiency and lower fuel use. Notably, many existing global trade routes and corridors were established several decades ago, during a period when carbon sensitivity among policymakers and industry stakeholders was minimal or deprioritized. As a result, these routes often reflect outdated priorities focused solely on economic efficiency or geopolitical considerations, without accounting for their environmental consequences. Reconfiguring

such routes with an emphasis on carbon reduction presents a significant opportunity to lower emissions in fiber trade logistics.

Third, the establishment of regional supply chain hubs can reduce reliance on long-distance transport, particularly in high-production regions such as Southeast Asia for synthetic fibers. Regionalization not only shortens trade distances but also facilitates more efficient distribution networks and fosters intra-regional trade.

Fourth, supporting the transition to clean energy in transportation, including the adoption of green shipping technologies and low-emission trucking fleets, is essential to curbing emissions along fiber trade routes. Finally, incentivizing multi-modal transport solutions that integrate maritime, rail, and road logistics can optimize supply chain operations, reduce carbon intensity, and enhance the overall sustainability of fiber trade logistics.

These operational strategies, directly informed by the findings of the environmental gravity model, represent practical pathways for reducing the carbon footprint associated with long-distance fiber trade, thereby contributing to the broader goal of sustainable and low-carbon international trade.

## Conclusion

This study provides a comprehensive analysis of the carbon footprint embodied in the global trade of eleven fibers, spanning eight natural and three synthetic types, over the period 2000 to 2022 and across 166 countries. Employing a novel Environmental Gravity Model (EGM), this research investigates environmental degradation in the context of international trade, focusing on the interplay between trade weight, trade distance, and trade value as key determinants of carbon emissions. The results demonstrate that synthetic fibers, due to their inherently high production-related emissions and greater sensitivity to trade-related factors, impose a disproportionately larger environmental burden compared to natural fibers.

Key findings reveal significant disparities in the environmental impacts of different fiber types. Synthetic fibers, such as Polyester, Acrylic, and Polyamide, exhibit the highest elasticities with respect to trade weight and distance, amplifying their carbon footprint as global trade expands. Conversely, natural fibers like Bamboo and Hemp show comparatively lower baseline emissions, reflecting their more sustainable production processes. However, certain natural fibers, such as Wool and Silk, also exhibit notable carbon footprints due to their production and long-distance transportation requirements.

These findings underscore the urgent need for targeted policy interventions. Promoting the adoption of low-carbon technologies in the production of synthetic fibers, optimizing transport logistics, and encouraging the development of regional supply chain hubs can significantly reduce emissions. Additionally, expanding the use of more sustainable natural fibers and improving supply chain efficiency are critical to mitigating the environmental impact of fiber trade.

The study's robustness check, which includes a binary fiber type dummy variable, provides additional evidence that natural fibers are systematically associated with lower embodied carbon emissions, independent of trade volume, weight, and distance. This finding strengthens the case for differentiated policy strategies that prioritize sustainable fiber sourcing and promote low-carbon transportation solutions.

Future research could extend this study by examining region-specific trade patterns, incorporating detailed transportation mode data, and assessing the integration of renewable energy in fiber production and logistics. Such efforts would enhance understanding of the pathways toward a more sustainable global fiber trade system and inform evidence-based trade and environmental policy.

## Limitations

While this study offers valuable insights into the carbon footprint embodied in global fiber trade, certain limitations should be acknowledged to contextualize the findings and inform future research directions.

First, the dataset employed in this study was sourced from the Chatham House Resource Trade Database, which provides comprehensive bilateral trade data, including associated carbon footprints, up to the year 2022. Due to the lack of updated data for subsequent years, the analysis is limited to this time frame. As more recent data become available, future studies could extend the temporal coverage to capture evolving trade patterns and policy impacts post-2022.

Second, the Environmental Gravity Model (EGM) applied in this study is subject to inherent assumptions typical of gravity-based approaches. Specifically, the calculation of trade distances is based on the linear distance between the capital cities of trading countries. While this method provides a standardized measure for bilateral distances, it does not account for the actual logistics routes or specific trade corridors utilized in practice. Consequently, variations arising from regional port access, infrastructure differences, and logistical routing are not explicitly captured.

Third, the model does not differentiate between transportation modes (e.g., maritime, air, rail, and road) due to data limitations. As a result, the varying carbon intensities associated with different transport modalities are not incorporated into the analysis. Given the significant disparity in emissions between transport modes, this is a notable area for further refinement.

Finally, the model does not account for the influence of green policy implementations, local and global incentives, or regulatory frameworks aimed at reducing the environmental impact of international trade. Incorporating such variables poses considerable challenges due to inconsistencies in measurement, limited data availability, and the diverse nature of environmental policy instruments across countries and regions. Future research could address these challenges by integrating policy indicators, carbon pricing mechanisms, and regulatory compliance measures into the analysis.

Despite these limitations, the study provides a robust and spatially explicit assessment of the carbon footprint embodied in global fiber trade, offering a valuable foundation for future research and policy development.

## Notes

1. <https://green-tailor.com/natural-vs-synthetic-fibers>.
2. These distances are used as a standardized proxy for trade routes between countries. While this method provides consistency across country pairs, it does not capture the actual logistics pathways or modes of transport used in fiber trade. This simplification is necessary due to data limitations and provides an approximate measure of the role of distance in transportation-related carbon emissions.
3. [https://www.trademap.org/Country\\_SelCountry\\_MQ\\_TS.aspx](https://www.trademap.org/Country_SelCountry_MQ_TS.aspx).

## Highlights

- **Novel Analytical Approach:** This study introduces a novel methodology for examining environmental degradation by employing an environmental gravity model. It uniquely analyzes the carbon footprint embodied in global fiber trade across 166 countries over a 22-year period (2000–2022).
- **Synthetic Fiber Carbon Footprint:** Synthetic fibers, such as polyester, acrylic, and polyamide, impose a significant environmental burden due to their energy-intensive production processes and sensitivity to trade-related factors.
- **Natural Fiber Emissions:** While bamboo and hemp demonstrate lower carbon footprints, natural fibers such as cotton, wool, and silk generate notable emissions, primarily driven by production and transport activities.
- **Trade Distance Amplification:** Trade distances substantially elevate carbon footprints, underscoring the need for optimized transport logistics. Synthetic fibers typically involve shorter trade distances, likely due to production near industrial hubs.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

## Data availability statement

The data used in this study are publicly available in the Chatham House Resource Trade Database (CHRTD) database at <https://resourcetrade.earth>. and <https://www.trademap.org>.

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