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Impact of environmental policies, regulations, technologies, and renewable energy on environmental sustainability in China's textile and fashion industry

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In this study, we bridge a crucial gap in the literature by investigating the interplay between environmental regulations, technological innovations, and renewable energy adoption and their impact on sector-specific environmental performance in the textile and fashion industry. Leveraging time series data from 1995 Q1 to 2022 Q4 and using autoregressive distributed lag (ARDL) and Granger causality techniques, this research is built upon the environmental Kuznets curve (EKC) hypothesis and regulatory push innovation hypothesis to unravel these complex interactions. Our findings demonstrate that rigorous environmental regulations and taxes are pivotal in enhancing environmental outcomes across various industry sectors, leading to significant reductions in greenhouse gas emissions and particulate matter. However, the total leather and feather production (LFP) and total fashion production (FP) sectors are highly responsive to environmental policy and regulations. Although technological advancements and research and development (R&D) initially increase ecological footprints due to high upfront costs, they are indispensable for achieving long-term environmental improvements and reshaping regulatory landscapes. The adoption of renewable energy sources, meanwhile, delivers immediate and substantial reductions in carbon emissions, highlighting their critical role in advancing industry sustainability. In this study, we advocate for leveraging environmental regulations as drivers of technological innovation and sustainability, urging policymakers to implement incentives for technological progress and renewable energy adoption. The implications of this research are significant for both industry stakeholders and policymakers. By positioning environmental regulations as catalysts for technological advancement, in this study, we emphasize the importance of a proactive, integrated approach to sustainability. Despite the study's regional focus, which may limit generalizability, future research should include longitudinal and comparative analyses across varied regions and emerging technologies to refine strategies for superior environmental performance.

KEYWORDS

environmental policy, environmental taxes, renewable energy, greenhouse gas emissions and air pollutants, ecological footprint, environmental efficiency

Introduction

China's textile and fashion industry, commanding a substantial 31.7% of global clothing exports in 2022 (DFU, 2023; Li et al., 2021), is a cornerstone of its economic framework, driving significant growth and providing extensive employment opportunities both domestically and internationally (Rafiq et al., 2023; Yang et al., 2023). However, China's textile and fashion industry is a significant contributor to negative externalities, particularly environmental degradation. The industry faces severe environmental challenges. It is a major source of greenhouse gas (GHG) emissions due to its energy-intensive production processes, and it significantly contributes to air pollution through high levels of particulate matter (PM2.5 and PM10), which are detrimental to the air quality and ecological footprint (Minlah and Zhang, 2021; Peng et al., 2022; Zhao and Lin, 2019). The industry's ecological footprint is also exacerbated by excessive water use, pollution from dyeing and finishing processes, and substantial waste generation (Herbst, 2021; Lu, 2021). To address these challenges, the Chinese government has enacted a suite of policies aimed at reducing the sector's environmental impact. These include regulations to improve energy efficiency, lower emissions, and adopt cleaner production techniques. The 14th Five-Year Plan (FYP) (2021–2025) outlines a greener textile and fashion industry strategy by promoting a circular economy, advancing technological innovations, and implementing stringent pollution controls (Gao et al., 2022; Xu et al., 2024). Environmental taxes have also been introduced to incentivize emissions and reduce resource use, supporting China's goal of achieving carbon neutrality by 2060 (Ruggerio, 2021).

Environmental regulation has become a crucial instrument in addressing these issues during periods of rapid economic development (Zhang H. et al., 2022). By 2013, China had established 30 national laws, over 1,400 industrial standards, and 314 local regulations related to environmental governance (Zheng and Shi, 2017). Implementing a stringent environmental protection law in 2015 further advanced the country's regulatory framework. Despite these measures, the efficacy of China's environmental regulations remains insufficient (Zhang H. et al., 2022). The 2020 Global Environmental Performance Index (EPI) ranked China 120th out of 180 countries in air quality, indicating ongoing pollution challenges. These persistent issues are primarily due to the incomplete implementation of central government policies at the local level, which is a phenomenon known as the "implementation gap" (Zhao et al., 2022).

Despite recent policy initiatives, significant gaps persist in understanding the environmental impact of China's textile and fashion industry. Theoretically, the environmental Kuznets curve (EKC) model, which suggests that environmental degradation initially increases with economic growth but decreases as economies mature, inadequately addresses the complexities of this sector. The interplay among policy measures, technological advancements, and regulatory frameworks presents a more intricate scenario than the EKC model encompasses (He et al., 2021; Zhang et al., 2022b). This underscores the need for a comprehensive framework to better grasp the sector's environmental performance. Key questions include how current environmental policies influence efficiency and whether these policies effectively drive improvements in the industry's environmental impact. A significant conceptual gap exists in understanding how technological advancements and renewable energy adoption interact within policy frameworks, as current literature often isolates these factors and neglects their combined impact on environmental efficiency (Fernández et al., 2018). Moreover, the role of environmental policies, taxes, research and development (R&D), and renewable energy across different textile and fashion sectors remains underexplored. This integration is crucial for assessing how these elements collectively influence regulatory effectiveness. Additionally, the specific effects of environmental taxes on the textile and fashion industry are insufficiently examined. Understanding how these taxes impact industry practices is essential for evaluating their effectiveness and refining policy design (Ruggerio, 2021).

Empirical research on environmental regulations often overlooks the specific response of China's textile and fashion industry, particularly concerning the effects of environmental taxes and the role of R&D in driving technological innovation. Additionally, the impact of renewable energy adoption on the industry's ecological footprint remains insufficiently examined (Chen et al., 2021; Leal Filho et al., 2022). This underscores the need for targeted studies to better understand how regulatory measures, technological advancements, and renewable energy integration collectively influence environmental performance. Furthermore, the interaction between technological innovation and policy frameworks, particularly in relation to the impact of renewable energy adoption on environmental efficiency, warrants comprehensive exploration. A deeper understanding of these critical areas is vital for crafting more effective and informed policy strategies.

The findings reveal that stringent environmental regulations and taxes are potent drivers of sustainable practices, significantly reducing greenhouse gas emissions and particulate matter. Although technological advancements, particularly in environmental technologies and R&D, are vital, they initially increase the industry's ecological footprint due to high costs and adjustments. However, the transition to renewable energy is pivotal for substantial long-term reductions in carbon emissions. The LFP and FP sectors exhibit notably higher coefficients related to GHG emissions and environmental pollutants than other textile and fashion sectors, underscoring the substantial impact of policy implementation in these areas. This finding highlights the effectiveness and prioritization of environmental regulations within these sectors, signaling a critical focus on mitigating environmental impact through targeted policy measures. The necessity of an integrated regulatory framework that harmonizes policy, technology, and renewable energy to achieve sustained environmental improvements is emphasized the study. Furthermore, a dynamic, reciprocal relationship between technological progress and regulatory advancements is highlighted, where each fosters the other's evolution, creating a reinforcing cycle essential for long-term environmental sustainability.

This study significantly advances our understanding of environmental sustainability within China's textile and fashion industry by offering a sector-specific analysis of the total textile production, leather and feather production, fashion production, and combined textile and fashion production. By examining the textile and fashion sectors, the study addresses crucial questions about the varying impacts of policies, technologies, and renewable energy adoption on environmental efficiency. It reveals that whereas environmental policies and taxes broadly enhance the efficiency, the effectiveness of technological innovations and renewable energy adoption differs significantly across industry segments, depending on their unique characteristics and practices. It fills a critical gap by revealing how different segments respond to environmental regulations and innovations, providing a comprehensive view of the industry's environmental performance. The study extends the EKC model and the regulatory push innovation hypothesis, demonstrating how regulatory measures and technological advancements uniquely interact within the textile sector to influence environmental outcomes. By integrating the effects of technological innovation, R&D, and renewable energy adoption, this research presents a holistic framework that illustrates the combined impact of these factors on environmental efficiency. Empirically, it clarifies the role of environmental policies and taxes in driving technological innovation and promoting cleaner production practices. It also highlights the significant benefits of renewable energy adoption in reducing the industry's ecological footprint. The study's theoretical implications challenge simplified assumptions, advocating for an integrated approach to environmental management. Practically, it provides actionable insights for policymakers and industry leaders, emphasizing the need for cohesive strategies that combine stringent regulations, supportive policies, and technological investments to drive sustainability and enhance competitiveness.

Theoretical framework

The theoretical foundation of environmental regulation is grounded in frameworks that explore how regulatory policies shape industrial behavior, innovation, and economic performance. A key theory in this domain is the EKC hypothesis, which posits an inverted U-shaped relationship between environmental degradation and economic development. According to this model, in the initial stages of economic growth, industrialization and increased consumption lead to an increase in environmental pollutants and resource depletion. The trend reverses as an economy continues to expand and reaches a certain threshold of income *per capita* (Minlah and Zhang, 2021). Higher levels of income facilitate greater investment in cleaner technologies, enhance public demand for environmental quality, and enable the implementation of more stringent regulatory measures. Consequently, further economic growth contributes to reducing pollutants and improving environmental conditions. The EKC suggests that increased economic pressures and regulatory measures can improve environmental outcomes over time (Zhang et al., 2022b). This framework implies that sufficient economic advancement and appropriate policy frameworks can achieve both continued economic growth and enhanced environmental quality. Thus, the EKC underscores the potential for harmonizing economic development with environmental sustainability through targeted regulatory and technological strategies.

Complementing this view are theories of sustainable development and industrial ecology. Sustainable development theory advocates for a balance between economic growth, environmental protection, and social equity, integrating environmental considerations into industrial policy to promote practices that reduce resource consumption and environmental impact (Ruggerio, 2021). Industrial ecology extends this by viewing industrial systems as part of a broader ecological system, emphasizing closed-loop systems and resource optimization to minimize waste and environmental footprints. Together, these frameworks provide a comprehensive lens for examining how stringent environmental regulations in China's textile and fashion industry can drive innovation, improve environmental performance, and support sustainable economic development.

Building on the foundational theories outlined above, this study introduces several key theoretical assumptions that further deepen our understanding of how environmental regulations shape industrial behavior and performance, particularly in the context of China's textile and fashion industry. One critical assumption is the regulatory push innovation hypothesis, which posits that stringent environmental regulations act as a catalyst for innovation in industrial sectors (Bitat, 2018). In response to increasing regulatory pressures, firms are incentivized to adopt cleaner technologies, enhance operational efficiency, and develop sustainable processes. Drawing on Porter's hypothesis, which suggests that environmental regulations can drive firms to innovate and unlock new market opportunities, we argue that China's textile industry is no exception (Bibi et al., 2024). Faced with both domestic and international regulatory demands, firms are compelled to innovate in ways that improve their environmental performance while maintaining competitive advantage (Khan et al., 2023).

Another important assumption is that of policy synergy and interaction (Li et al., 2024). This assumption asserts that environmental regulations, technological innovation, taxes, and renewable energy policies interact synergistically to amplify their collective impact on sustainability. Rather than operating in isolation, these policy instruments reinforce each other, creating a comprehensive policy environment that accelerates the adoption of green technologies and practices. For instance, the effectiveness of renewable energy adoption in the textile industry can be significantly enhanced when paired with carbon taxes or green subsidies, facilitating the transition to more sustainable production methods. This assumption highlights the necessity for coherent and integrated policy frameworks to drive significant environmental improvements. Furthermore, we propose the dynamic interaction assumption, which draws on the EKC hypothesis to explain how economic growth and environmental regulations interact over time. As China's textile and fashion industry continues to grow, the initial phase of rapid industrialization often leads to environmental degradation. However, as the economy matures, a shift occurs, where firms, driven by consumer demand for sustainability and regulatory incentives, begin to adopt cleaner technologies and more sustainable practices. This dynamic shift underscores the potential for harmonizing economic growth with environmental sustainability through effective regulation and innovation.

Finally, the globalization assumption suggests that international pressures, particularly from global consumers and stakeholders (Baah et al., 2021; Christmann, 2004), significantly influence the environmental performance of the textile industry in China. With increasing demand for sustainable products in global markets, Chinese firms are compelled to align with international sustainability standards. This not only drives innovation and compliance with both domestic and foreign regulations but also reflects the broader phenomenon of environmental globalization. The increasing importance of international consumer preferences and regulatory frameworks compels industries worldwide to adopt sustainable practices, influencing the trajectory of environmental policy and performance in the Chinese textile sector. Together, these theoretical assumptions provide a comprehensive lens to examine the complex relationships among environmental regulations, innovation, and industry performance. By integrating these assumptions into our framework, we offer a more nuanced understanding of how regulatory pressures, economic growth, and globalization intersect to drive sustainable practices in China's textile and fashion industry.

Literature

Greenhouse gas emissions and ecological footprint in the textile industry

The textile industry significantly contributes to global GHG emissions, accounting for approximately 10% of global emissions annually (Leal Filho et al., 2022; European Parliament, 2020). This considerable impact stems from the sector's energy-intensive production processes and complex, often international, supply chains (Chen et al., 2021). Notably, the fashion industry alone is responsible for around 10% of global GHG emissions, surpassing the combined emissions of the aviation and shipping sectors (UNFCCC, 2018). Reducing these emissions is critical to meeting the Paris Agreement's goal of limiting global warming to 1.5°C above pre-industrial levels. In response, initiatives by the UN Climate Change Conference aim to unify industry stakeholders—from raw material producers to apparel brands—to expand climate mitigation efforts across the value chain (UNFCCC, 2024).

The rise of the fast fashion model has exacerbated the textile industry's environmental impact, with predictions that the fashion sector could consume up to 25% of the world's carbon budget by 2050 due to increased natural resource consumption driven by increasing clothing demand (Berg et al., 2019; Peng et al., 2022). Between 2010 and 2020, global fiber production almost doubled from 58 to 109 million tons, highlighting the industry's expanding environmental footprint (TextileExchange, 2021). The Chinese textile industry alone accounted for 6.02% of all industrial carbon emissions in 2015 (Lin et al., 2018; Peng et al., 2022). GHG emissions from this sector include not only CO_2 but also potent gases like methane (CH4) and nitrous oxide (N2O), released during production and waste management (Zhang J. et al., 2020). The disposal of approximately 26 million tons of used apparel in Chinese landfills annually further contributes to these emissions (Lee et al., 2018; Peng et al., 2022).

Socioeconomic factors, including consumption patterns, energy depletion, and inefficient waste management, are major drivers of GHG emissions in the textile industry (Wang et al., 2017; Zhang et al., 2018). Although strategies such as upgrading production techniques, promoting clean production practices, and enhancing energy efficiency have been proposed to reduce emissions (Lin and Zhao, 2016; Oelze, 2017), their application within China's textile industry remains limited, particularly in achieving carbon neutrality. Furthermore, the impact of climate policies like carbon pricing on the textile industry is underexplored, especially in China. Although such policies have been extensively studied in other sectors, their implications for textiles are not well understood (Clark et al., 2020; Zheng and Suh, 2019). Addressing these gaps requires integrated assessments considering the combined effects of environmental policies, technological advancements, and socioeconomic changes on GHG emissions within the textile industry. Understanding these interactions is essential for formulating effective strategies to reduce the carbon footprint of the textile and fashion sectors and contribute to global climate change-mitigation efforts.

The textile industry also exerts a significant ecological footprint through its intensive resource consumption, pollution, and waste generation. For example, producing a single cotton shirt can require up to 2,700 L of water, whereas the sector's reliance on fossil fuels exacerbates its environmental impact (European Parliament, 2020). To mitigate these effects, advancements in waterless dyeing technologies, energy-efficient machinery, and the adoption of sustainable materials and recycling practices are essential. These innovations highlight the ongoing need for responsible practices within the industry. Environmental policies and taxes are crucial in shaping the textile industry's environmental performance. Higher environmental tax rates can incentivize green technology adoption, particularly in China's textile sector, potentially reducing its ecological impact. However, further exploration is needed to understand how varying levels of policy stringency affect sub-sectors like fashion, leather, and textiles. The role of private participation and green finance in promoting renewable energy adoption is equally critical; yet, the integration of these policies with sector-specific regulations and technologies remains under-researched (Wang and Yu, 2021; Zhang et al., 2022c).

Technological innovations, especially Industry 4.0 technologies, are vital for minimizing the ecological footprint of textiles by optimizing energy use and enhancing sustainability. Although digital tools have improved both economic and environmental performance, more research is needed to understand their specific impact on renewable energy integration within textile sub-sectors (Javaid et al., 2022; Li et al., 2020). To effectively reduce the industry's environmental impact, integrated assessments are required. These should consider the collective effects of environmental policies, technological advancements, and renewable energy adoption across various sub-sectors, offering a comprehensive approach to mitigating the textile industry's ecological footprint (Huong and Thanh, 2022; Pandey et al., 2023) (see Supplementary Table A1 and Supplementary Table A3 for more details on the literature gap).

Textile industry and air pollutants

The textile and fashion industry significantly contributes to air pollution by releasing fine particulate matter (PM2.5 and PM10). In China, the world's fastest growing developing country, this industry not only plays a crucial economic role but also poses severe environmental challenges, particularly in terms of air quality (Liu et al., 2021; Liu et al., 2017). Textile-related activities account for nearly one-third of PM2.5 emissions in China, making it a major contributor to the country's air pollution crisis (Zhang F. et al., 2020; Zhang and Chen, 2020). These particles, with diameters of 2.5 and 10 μm, respectively, are primarily generated from dust, smoke, and chemical compounds released during textile manufacturing, particularly in coal-reliant mills (Mahmud et al., 2024; Shahriar et al., 2020).

PM2.5 and PM10 pose significant health risks, including respiratory and cardiovascular diseases, and exacerbate environmental degradation. Despite efforts by the Chinese government, such as the National Ambient Air Quality Monitoring Network (NAAQMN), haze pollution driven by these particulates remains a critical issue, particularly in urban areas (Liu et al., 2021; Xu et al., 2021). Moreover, the fashion industry, recognized globally as one of the most polluting sectors, exacerbates these challenges with its vast water consumption and pollutant discharge, contributing 20% of the world's wastewater from fabric dyeing and treatment (Saha et al., 2022).

However, there is a significant research gap concerning sector-specific studies within China's textile and fashion industry. The current literature lacks empirical assessments that disaggregate the industry into sub-sectors—TMU, WAU, LFU, and TT—to evaluate the environmental impacts of policies, taxes, and renewable energy adoption on air pollutants like PM2.5 and PM10. The aim of this study was to address these gaps by providing detailed, sector-level empirical evidence, thus contributing to a more comprehensive understanding of the textile industry's role in air pollution and informing targeted policymaking for sustainable development (Khan et al., 2023; Xu et al., 2023; Yuan and Zhang, 2020; Zhang et al., 2020a) (see Supplementary Table A2 and Supplementary Table A3 for more details on the literature gap).

Environmental policy, taxes, and R&D in China's textile and fashion industry

China's rapid economic growth has led to significant environmental challenges, particularly in energy-intensive sectors like the textile and fashion industry, where excessive fossil fuel consumption has resulted in severe pollution (Dong et al., 2020; Feng and Yuan, 2021). In response, the Chinese government has increasingly focused on implementing environmental policies, taxes, and R&D initiatives to improve sustainability within these industries (Chen et al., 2021; Xue et al., 2022).

Historically, China's environmental policies have evolved from command-and-control measures, which, although easy to be implemented, often resulted in economic inefficiencies (Xue et al., 2022). The shift toward market-based approaches, such as cap-and-trade mechanisms and environmental taxes, represents a more efficient strategy for reducing pollution. The 2018 Environmental Protection Tax Law marked a significant step in this direction; however, areas remain for improvement, particularly concerning tax rates and clarity for taxpayers (Jiang et al., 2023; Peng et al., 2021).

Policy stringency is crucial in driving sustainable practices, especially in high-impact sectors like textiles and fashion (Usman et al., 2024). The strictness and enforceability of environmental regulations can vary, but China has developed a comprehensive environmental governance system that involves multiple actors and policy instruments (Shen et al., 2020). Studies indicate that China's environmental policies have significantly progressed, moving from tax regulations to more stringent frameworks due to growing environmental challenges, particularly severe air and water pollution (Zhang et al., 2022c).

In addition to regulatory measures, the Chinese government has introduced preferential R&D tax policies to promote green innovation within industries. These incentives aim to reduce the costs and risks associated with developing environmentally friendly products (Bai et al., 2019). Whereas some studies affirm the positive impact of these tax incentives (Stucki et al., 2018), others suggest that regulatory constraints may limit their effectiveness, potentially leading to rent-seeking behavior or crowding out private R&D investments (Jia et al., 2020; Jia and Ma, 2017).

China's stricter environmental regulations, such as the "Green Development" policies in its 13th and 14th Five-Year Plans, have targeted the textile industry's environmental impact by encouraging energy efficiency, waste reduction, and renewable energy adoption (Zheng et al., 2022). However, the effectiveness of these policies has been mixed, with enforcement inconsistencies, particularly at the local level, where economic pressures often result in regulatory leniency (Liu et al., 2017; Zhang J. et al., 2020).

The impact of environmental taxes on CO_2 emissions and air pollutants has been well studied, with some research highlighting their potential to reduce emissions and foster economic growth, especially when combined with investments in technology and renewable energy (He et al., 2021; Sharif et al., 2023). Conversely, regional growth in certain sectors can enhance CO_2 emissions, underscoring the need for innovative measures and continued investment in R&D (Nosheen et al., 2021).

Despite these efforts, research on the combined effects of environmental policies, taxes, R&D, and renewable energy adoption on the environmental performance of China's textile and fashion industry remains limited. The existing literature often addresses these elements in isolation, leaving a gap in understanding their interactive impact on sustainable industrial practices. Therefore, a more integrated approach is needed to optimize these measures for greater sustainability within this

TABLE 1 Variable units, notation, and sources.

Variable	Notation	Definition	Unit	Data source
GHG emissions	GHG	(tCO_2e *per capita* total GHG emissions) tons of carbon dioxide equivalent	Tons	OECD
PM2.5	PM2.5	Fine particulate matter that is 2.5 μ or less in diameter	Tons	OECD
PM10	PM10	Particulate matter with a diameter of 10 μm or less	Tons	OECD
Ecological footprint	EFP	Ecological footprint measures whether humanity lives within the means of nature. An EFP of less than 1.6 global hectares per person makes the resource demand globally replicable	Global hectares (gha)	Global footprint network database
Total textile and fashion production	TTP	Total textile, apparel, leathers, and accessories manufacturing units	Numbers	China's Statistical Yearbook
Total textile production	TMP	Textile manufacturing units	Numbers	China's Statistical Yearbook
Total fashion production	FP	Weaving, apparel, and accessories units	Numbers	China's Statistical Yearbook
Total leather and feather production	LFP	Leather, fur, and feather-related products units	Numbers	China's Statistical Yearbook
Environmental policy implementation	EPC	Environmental Policy Stringency Index (EPSI)	0–6	OECD Database
Environmental laws (regulations)	ER	Environmentally related revenues (% of GDP, converted into US$)	US$	OECD Database
Renewable energy supply	REG	Percent of total energy production, % total energy supply	% points	OECD Database
Research and development	R&D	% GDP (% point converted into US$) – scientific infrastructure	% points	OECD Database
Economic growth	PGDP	GDP *per capita* is the gross domestic product divided by mid-year population. Data are in constant 2015 US dollars	US$	World Bank database
Environmental innovations/ technologies	ET	Environment-related patents	Number	OECD Database

resource-intensive and pollution-prone industry (see Supplementary Table A4 and Supplementary Table A3 for more details on the literature gap).

Methodology

Various sets of variables were used in this study to examine the impact of environmental policies, taxes, renewable energy supply, environmental technologies, economic growth (*per capita* GDP), and R&D on the environmental performance of textile and fashion industry sub-sectors. Many studies broadly explore the environmental impacts of industries, but few have provided a sector-specific analysis within the textile and fashion industry. Most existing studies tend to focus on one or two factors (e.g., technology or policy) affecting environmental performance. This research contributes by offering an integrated assessment that includes policies, taxes, technologies, and renewable energy. Time series data collected from 1995 Q1 to 2022 Q4 were used in this study to address the mentioned literature. The dependent variables include total GHG emissions, PM2.5, PM10, and ecological footprint. The independent variables comprised the textile and fashion industry's sectors (TMP, LFP, FP, and TTP), environmental policy, taxes, R&D, PGDP, and renewable energy (REG) (see Table 1 for more details).

All the variables were transformed into their logarithmic form to achieve normality. We applied unit root tests proposed by Phillips and Perron (1988) and Dickey and Fuller (1979) to verify the stationarity of the variables. Descriptive statistics (Table 2) (supplementary) shows that the kurtosis (−7, +7) and skewness (−2, +2) were within the threshold range established by Byrne and Van de Vijver (2010), indicating the variables' normality. Table 3 (supplementary) indicates that all the variables are stationary either at I(0) or I(1), or both.

We used an autoregressive distributed lag (ARDL) bounds test approach to examine the long-term cointegration among four textile and fashion industry sub-sectors, environmental policy, environmental taxes, renewable energy supply, R&D, greenhouse gas emissions, PM2.5, PM10, ecological footprint, and economic growth. Additionally, the vector error correction (VEC) model was utilized to analyze the direction of causality among these variables, following the methodology outlined by Granger (Khan et al., 2020). Our analysis commenced with the development of a general multivariate linear regression model represented by Equation 1:

$$Y_i = f\ (X_{1i}, \ldots\ldots\ldots, X_{4i}, \ldots\ldots\ldots\ldots\ X_{ni}), \qquad (1)$$

where *Yi* in Equation 1 denotes dependent variables such as greenhouse gases, air pollutants, ecological footprint, and energy consumption, and *X1i*, ... *X4i* . . . . *Xni* represent independent variables, including textile and fashion industry sub-sectors, environmental policy, taxes,

TABLE 2 Descriptive statistics.

	EPC	ER	ET	PGDP	REG	TMP	LFP	R&D	FP	TTP	GHG	PM2.5	PM10	EFP
Mean	3.91	24.46	10.22	8.05	2.47	9.88	8.81	25.17	9.45	11.20	1.75	16.14	16.54	0.96
Median	3.97	25.13	10.39	8.20	2.32	9.86	9.00	25.36	9.48	11.30	1.89	16.21	16.59	1.00
Maximum	5.24	25.73	12.05	9.60	3.06	11.33	10.03	26.68	10.78	12.22	2.16	16.28	16.65	1.34
Minimum	1.20	21.66	7.80	6.41	2.01	9.20	8.04	23.01	8.66	9.81	1.17	15.91	16.37	0.57
Std. dev.	1.23	1.36	1.44	1.03	0.36	0.43	0.45	1.15	0.41	0.80	0.39	0.13	0.10	0.29
Skewness	−0.62	−1.00	−0.22	−0.13	0.54	1.10	−0.07	−0.36	0.54	−0.37	−0.46	−0.59	−0.57	−0.17
Kurtosis	2.34	2.54	1.62	1.50	1.72	2.63	3.46	1.84	2.23	1.80	1.51	1.72	1.73	1.38
Jarque–Bera	1.23	1.82	1.83	1.88	1.02	4.97	1.09	1.79	1.71	1.28	1.27	1.13	1.55	1.47
Probability	0.33	0.13	0.13	0.18	0.61	0.00	0.58	0.11	0.21	0.45	0.43	0.75	0.32	0.41
Observations	112	112	112	112	112	112	112	112	112	112	112	112	112	100

TABLE 3 Stationarity test.

Variable	Augmented Dickey–Fuller		Phillips–Perron		Level of integration
	Level	Difference (1)	Level	Difference (1)	
EPC	−2.09	−10.95*	−2.22	−10.95*	I (1)
ER	−2.45	−3.06**	−2.43	−11.25*	I (1)
ET	−1.53	2.17	−1.73	−13.01*	I (1)
PGDP	−3.38***	−1.27	−0.51	−13.54*	I (0) and I (1)
REG	−1.87	−1.57	−1.67	−11.56*	I (1)
R&D	−3.10**	−3.29***	−3.58*	−14.34*	I (0) and I (1)
TMP	−2.70***	−7.71*	−2.52	−11.87*	I (0) and I (1)
LFP	−2.12	−8.23*	−2.34	−15.01*	I (1)
FP	−2.42	−8.43*	−2.69***	−15.13*	I (0) and I (1)
TTP	−3.44***	−7.73*	−3.27***	−18.77*	I (0) and I (1)
GHG	−1.88	1.75	−1.05	−11.81*	I (1)
PM25	−1.39	−2.90**	−0.85	−10.86*	I (1)
PM10	1.35	−2.98**	−0.91	−10.82*	I (1)
EFP	−0.54	−2.14	−0.45	−11.17*	I (1)

Note: *, **, and *** denote the significance level at 1%, 5%, and 10%, respectively.

technology, *per capita* GDP, renewable energy supply, and R&D. Following this, the bounds test cointegration approach, as proposed by Pesaran et al. (2001), was used to assess long-run associations. Cointegration was determined by comparing the calculated F-statistic to the tabulated critical values.

The ARDL bounds test offers several advantages over traditional methods, including its capacity to handle variables with different stationarity levels and its adjustment for serial correlation (Khan et al., 2020). Unlike the cointegration methods suggested by Engle and Granger (1987) and Johansen and Juselius (1990), which are limited by stationarity constraints, the bounds test can be applied to variables that are either I(0) or I(1) but not I(2) (Khan et al., 2020). This method presumes long-term cointegration among the variables, and a dynamic error correction model (ECM) can be developed to integrate both long- and short-term dynamics without losing data (Nepal et al., 2019).

The ECM is specified as follows in Equation 2:

$$\begin{aligned}\Delta Y_{ti} = \delta_0 + \sum_{i=1}^{n}\delta_{1i}\Delta Y_{ti-i} + \sum_{i=1}^{n}\delta_{2i}\Delta X1_{ti-i} + \sum_{i=1}^{n}\delta_{3i}\Delta X2_{ti-i} + \ldots\ldots\ldots\ldots \\ + \sum_{i=1}^{n}\delta_{ni}\Delta Xn_{ti-i} + \delta_5 Y_{ti-1} + \delta_{6i}\Delta X1_{ti-1} + \delta_{7i}\Delta X2_{ti-1} \\ + \ldots\ldots\ldots\ldots\ldots\ldots + \delta_{ni}\Delta Xn_{ti-1}\,. \end{aligned} \tag{2}$$

TABLE 4 Bounds test for co-integration for different textile and fashion sectors.

ARDL model	F-static-*p*	Critical bounds value		
		1%	5%	10%
GHG emissions				
GHG f (GHG | EPC, ER, ET, PGDP, REG, R&D, and TMP)	6.82*	2.96–4.26	2.23–3.50	2.03–3.13
GHG f (GHG | EPC, ER, ET, PGDP, REG, R&D, and LFP)	19.15*	2.96–4.26	2.23–3.50	2.03–3.13
GHG f (GHG | EPC, ER, ET, PGDP, REG, R&D, and FP)	17.14*	2.96–4.26	2.23–3.50	2.03–3.13
GHG f (GHG | EPC, ER, ET, PGDP, REG, R&D, and TTP)	14.93	2.96–4.26	2.23–3.50	2.03–3.13
PM2.5 emissions				
PM2.5 f (PM2.5 | EPC, ER, ET, PGDP, REG, R&D, and TMP)	8.24*	2.96–4.26	2.23–3.50	2.03–3.13
PM2.5 f (PM2.5 | EPC, ER, ET, PGDP, REG, R&D, and LFP)	22.91*	2.96–4.26	2.23–3.50	2.03–3.13
PM2.5 f (PM2.5 | EPC, ER, ET, PGDP, REG, R&D, and FP)	20.95*	2.96–4.26	2.23–3.50	2.03–3.13
PM2.5 f (PM2.5 | EPC, ER, ET, PGDP, REG, R&D, and TTP)	10.35*	2.96–4.26	2.23–3.50	2.03–3.13
PM2.10 emissions				
PM10 f (PM10 | EPC, ER, ET, PGDP, REG, R&D, and TMP)	6.45*	2.96–4.26	2.23–3.50	2.03–3.13
PM10 f (PM10 | EPC, ER, ET, PGDP, REG, R&D, and LFP)	17.61*	2.96–4.26	2.23–3.50	2.03–3.13
PM10 f (PM10 | EPC, ER, ET, PGDP, REG, R&D, and FP)	14.97*	2.96–4.26	2.23–3.50	2.03–3.13
PM10 f (PM10 | EPC, ER, ET, PGDP, REG, R&D, and TTP)	8.53*	2.96–4.26	2.23–3.50	2.03–3.13
Ecological footprint				
EFP f (EFP | EPC, ER, ET, PGDP, REG, R&D, and TMP)	5.21*	2.96–4.26	2.23–3.50	2.03–3.13
EFP f (EFP | EPC, ER, ET, PGDP, REG, R&D, and LFP)	5.07*	2.96–4.26	2.23–3.50	2.03–3.13
EFP f (EFP | EPC, ER, ET, PGDP, REG, R&D, and FP)	5.33*	2.96–4.26	2.23–3.50	2.03–3.13
EFP f (EFP | EPC, ER, ET, PGDP, REG, R&D, and TTP)	5.19*	2.96–4.26	2.23–3.50	2.03–3.13

Note: *, **, and *** denote the significance level at 1%, 5%, and 10%, respectively.

Δ represents the first difference, and *Y* and *X* denote the dependent and independent variables, respectively. Cointegration is confirmed if the Wald test rejects the null hypothesis H0: δ6 = δ7 = …… = δn = 0. The short-run dynamics for the variables in Equation 1 were estimated using the ARDL models outlined in Equation 3:

$$\Delta Y_{ti} = \delta_0 + \sum_{i=1}^{p} \delta_{1i} \Delta Y_{ti-i} + \sum_{i=1}^{q1} \delta_{2i} \Delta X1_{ti-i} + \sum_{i=1}^{q2} \delta_{3i} \Delta X2_{ti-i} + \cdots\cdots\cdots + \sum_{i=1}^{qn} \delta_{ni} \Delta Xn_{ti-i}. \tag{3}$$

The long-run elasticities were estimated using Equation 4 and Equation 5:

$$a0 = \frac{ao}{1 - \sum_{i=1}^{Pti} a1, i}, \tag{4}$$

$$aj = \frac{am}{1 - \sum_{i=1}^{Pti} a1, i}. \tag{5}$$

However, j = 1,2. . ., 4 and m = 2, 3, . . . 6.

The error correction term was captured using Equation 6:

$$\Delta Y_{ti} = \delta_0 + \sum_{i=1}^{n} \delta_{1i} \Delta Y_{ti-i} + \sum_{i=1}^{n} \delta_{2i} \Delta X1_{ti-i} + \sum_{i=1}^{n} \delta_{3i} \Delta X2_{ti-i} + \cdots\cdots\cdots + \sum_{i=1}^{n} \delta_{ni} \Delta Xn_{ti-i} + \sum_{i=1}^{n} \delta_{ni} ECMn_{ti-1} + e_{ti}. \tag{6}$$

Model stability was verified using the cumulative sum (CUSUM) and cumulative sum of squares (CUSUMQ) tests (Page, 1954), with additional standard diagnostic tests to assess model validity. The VAR Granger causality test was then conducted to determine the direction of causality (Granger, 1969).

Results

Four multivariate equations were estimated each for GHG emissions, PM2.5, PM10, and ecological footprint. The ARDL bounds test approach was applied to examine cointegration between variables. As the ARDL bounds test is sensitive to lag length, the VAR lag length criteria were used to determine the appropriate lag length for each equation. Table 4 shows the bounds

TABLE 5 Textile and fashion industry sector-wise long- and short-run dynamics.

Variable	Greenhouse gas emission				PM2.5 emission				PM10 emission				Ecological footprint			
	GHG (TMP)	GHG (LFP)	GHG (FP)	GHG (TTP)	PM2.5 (TMP)	PM2.5 (LFP)	PM2.5 (FP)	PM2.5 (TTP)	PM10 (TMP)	PM10 (LFP)	PM10 (FP)	PM10 (TTP)	EFP (TMP)	EFP (LFP)	EFP (FP)	EFP (TTP)
Long-run																
EPC	−0.081*		−0.0312***		−0.125*	−0.061*	−0.075*	−0.055*	−0.117*	−0.033**	−0.066*	−0.044*				−0.018***
ER	−0.102*	−0.073*	−0.068*	−0.078*	−0.058*	−0.112*	−0.078*	−0.105*		−0.086*	−0.058*	−0.086*				
ET	0.083*	0.111*	0.099*	0.205*	0.091*		0.051*	0.172*	0.079*		0.039**	0.155*	0.215*	0.214*	0.205*	0.236*
PGDP	−0.377*	−0.399*	−0.390*	−0.385*	−0.189*	−0.236*	−0.234*	−0.254*	−0.139*	−0.244*	−0.203*	−0.227*				
REG	−0.567*	−0.564*	−0.588*	−0.487*	−0.346*	−0.403*	−0.408*	−0.289*	−0.252	−0.319*	−0.320*	−0.205*	−0.352*	−0.346*	−0.353*	−0.335*
R&D	0.622*	0.533*	0.518*	0.481*	0.276*	0.415*	0.335*	0.339*	0.198*	0.357*	0.283*	0.293*	−0.119**	−0.129**	−0.110**	−0.127**
TMP	−0.059*				−0.063*				−0.056*				−0.021***			
LFP		−0.101*				−0.123*				−0.126*				−0.022***		
FP			−0.091*				−0.107*				−0.102*				−0.028*	
TTP				−0.115*				−0.154*				−0.152*				−0.028***
Constant	−6.98*	−5.228*	−5.077*	−4.900*	13.109*	12.249*	13.198*	12.984*	14.18*	13.264*	14.005*	13.767*	2.615*	2.695*	2.512*	2.664*
Trend																
Short-run																
EPC	0.037*	−0.052*	0.045*	0.042*	−0.024*		0.0517*	0.0533*	−0.029*	0.041*	0.050*	0.039*				
ER	−0.09*	−0.073*	−0.055*	−0.072*	−0.058*	0.055*	−0.053*	−0.070*	−0.049*	−0.067*	−0.041*	−0.043*				
ET	−0.052**	−0.085*	−0.087*	−0.081*	0.082*	0.068*	0.079*	0.116*	0.063*	−0.011*	0.052**	0.098*	−0.115*	−0.109*	−0.114*	−0.117
PGDP	−0.109*	−0.087**	−0.082*	−0.084**	−0.168*	−0.206*	−0.146*	−0.202*	−0.134*	−0.158*	−0.116*	−0.234*				
REG	−0.568*	−0.628*	−0.596*	−0.604*	−0.382*	−0.508*	−0.435*	−0.501*	−0.299*	−0.435*	−0.349*	−0.417*	−0.378*	−0.377*	−0.379**	−0.366
R&D	−0.350*	−0.438*	−0.416*	−0.396*	−0.234*	−0.346*	−0.285*	−0.300*	−0.170*	−0.267*	−0.212*	−0.232*	−0.034**	−0.036*	−0.033*	
TMP	−0.033*				−0.037*				−0.030*				−0.018*			
LFP		−0.051*				−0.346*				−0.044*				−0.019*		
FP			−0.046*				−0.044				−0.035*				−0.020*	
TTP				−0.057*				−0.059*				−0.050*				−0.020*

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TABLE 5 (*Continued*) Textile and fashion industry sector-wise long- and short-run dynamics.

Variable	Greenhouse gas emission				PM2.5 emission				PM10 emission				Ecological footprint			
	GHG (TMP)	GHG (LFP)	GHG (FP)	GHG (TTP)	PM2.5 (TMP)	PM2.5 (LFP)	PM2.5 (FP)	PM2.5 (TTP)	PM10 (TMP)	PM10 (LFP)	PM10 (FP)	PM10 (TTP)	EFP (TMP)	EFP (LFP)	EFP (FP)	EFP (TTP)
Diagnostics																
A	0.927 (0.629)	0.286 (0.867)	0.255 (0.882)	0.165 (0.921)	0.271 (0.873)	0.177 (0.915)	2.947 (0.229)	9.143 (0.010)	0.504 (0.777)	1.831 (0.400)	1.010 (0.603)	1.365 (0.141)	1.79 (0.431)	1.92 (0.54)	1.232 (0.413)	1.461 (0.302)
B	1.662 (0.199)	1.341 (0.119)	1.901 (0.128)	1.454 (0.077)	1.217 (0.165)	2.08 (0.065)	1.789 (0.114)	1.925 (0.081)	1.947 (0.115)	1.196 (0.152)	1.780 (0.126)	1.844 (0.074)	0.854 (0.358)	0.37 (0.69)	0.587 (0.558)	0.508 (0.603)
C	1.048 (0.428)	1.554 (0.210)	1.294 (0.112)	1.815 (0.097)	2.135 (0.110)	1.39 (0.127)	1.270 (0.132)	1.713 (0.088)	1.183 (0.311)	1.078 (0.399)	1.602 (0.068)	1.704 (0.092)	0.303 (0.739)	0.28 (0.75)	0.204 (0.816)	0.258 (0.773)
Adjusted R^2	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
F-test (p)	5,012.3*	5,400.8*	5,160.4*	4,474.2*	883.23*	697*	828.7*	776.98*	559.7*	487.91*	503.68*	519.84*	7,395.1*	7,457.4*	7,954.8*	7,216.7*
CUSUM	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Unstable	Stable	Stable	Stable	Stable
CUSUM-Sq	Stable	Unstable	Stable	Unstable	Stable	Unstable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable
ECM	−0.561*	−0.723*	−0.707	−0.662*	−0.592*	−0.744*	−0.690*	−0.677*	−0.536*	−0.689*	−0.627*	−0.629*	−0.287*	−0.282*	−0.299	−0.292*

A = normality; B = Breusch–Godfrey serial correlation LM test; C = ARCH heteroskedasticity test; CUSUM, cumulative sums, CUSUM-Sq = cumulative sums of square; ECM, error correction model. Note: *, **, and *** denote the significance level at 1%, 5%, and 10%, respectively.

test results, indicating that all the estimated bounds test equations for GHG emissions, PM2.5, PM10, and EFP were cointegrated as the F-calculated values are greater than F-tabulated values (Khan et al., 2023).

Table 5 shows the textile and fashion industry's sector-wise long and short-run results. The long-run dynamics show that the equation estimated for TMP impacts on GHG emissions indicates that environmental policy controls (EPCs) with δ = −0.081*, ER with δ = −0.102*, REG with δ = −0.567*, PGDP with δ = −0.377*, and TMP with δ = −0.059* negatively influence GHG emissions in the TMP sector. The long-run assessment of the LFP sector indicates that environmental regulations (ER) with δ = −0.073*, REG with δ = −0.564*, PGDP with δ = −0.399*, and LFP with δ = −0.101* negatively impact GHG emissions. Likewise, the long-run results of the FP sector show EPC with δ = −0.0312***, ER with δ = −0.068*, REG with δ = −0.588*, PGDP with δ = −0.390*, and FP with δ = −0.091* also negatively influence GHG emissions. The fourth equation estimated for GHG emissions demonstrates that ER with δ = −0.078*, REG with δ = −0.487*, PGDP with δ = −0.385*, and TTP with δ = −0.115* indicate the environmental efficiency of these indicators. Interestingly, R&D and environmental technologies indicate positive impacts in all four equations estimated for GHG emissions (see Table 5).

Four additional equations were calculated to assess the impacts of environmental instruments on PM2.5 in the textile and fashion industry. Table 5 shows that EPC with δ = −0.125*, ER with δ = −0.058*, REG with δ = −0.487*, PGDP with δ = −0.189*, and TMP with δ = −0.063* negatively influence PM2.5. The long-run estimates indicate that EPC with δ = −0.061*, ER with δ = −0.112*, REG with δ = −0.403*, PGDP with δ = −0.236*, and LFP with δ = −0.123* negatively affect PM2.5 in the leather and feather production sector. The long-run dynamics for the fashion production sector indicate that EPC with δ = −0.075***, ER with δ = −0.105*, REG with δ = −0.408*, PGDP with δ = −0.234*, and FP with δ = −0.107* significantly influence PM2.5. Similarly, the long-run indicator for TTP shows that EPC with δ = −0.055*, ER with δ = −0.105*, REG with δ = −0.289*, PGDP with δ = −0.254*, and TPP with δ = −0.154* significantly influence PM2.5. Similar to GHG emissions, R&D and environmental technologies (ET) show a positive effect on PM2.5 in all four sectors.

The estimated equation for PM10 indicates that EPC with δ = −0.117*, REG with δ = −0.252*, PGDP with δ = −0.139*, and TMP with δ = −0.056* significantly influence PM10 in the textile production sector. The long-run estimates show that EPC with δ = −0.033**, ER with δ = −0.086*, REG with δ = −0.319*, PGDP with δ = −0.14*, and LFP with δ = −0.126* negatively influence PM10 in the LFP sector. The long-run impacts in the fashion sector indicate that EPC with δ = −0.066*, ER with δ = −0.058*, REG with δ = −0.320*, PGDP with δ = −0.203*, and FP with δ = −0.102* significantly influence PM10 emissions in the fashion production sector. The estimates for the TTP sector shows that EPC with δ = −0.044*, ER with δ = −0.086*, REG with δ = −0.205*, PGDP with δ = −0.227*, and TTP with δ = −0.152* significantly affect PM10 emissions.

The long-run dynamics for ecological footprint indicate that only REG with δ = −0.352*, R&D with δ = −0.119**, and TMP with δ = −0.021*** significantly influence EFP in the textile production sector. Likewise, REG with δ = −0.346*, R&D with δ = −0.129**, and LFP with δ = −0.022*** significantly influence EFP in the leather and feather production sector. The long-run indicators show that REG with δ = −0.353*, R&D with δ = −0.110**, and FP with δ = −0.028* significantly affect EFP in the fashion production sector. The long-run dynamics show that EPC with δ = −0.018***, REG with δ = −0.335*, R&D with δ = −0.127*, and TTP with δ = −0.028*** significantly influence EFP in the TTP sector. However, environmental technologies positively and significantly impact EFP in all four sectors.

The lower part of Table 5 shows the short-run results, equation diagnostics, and model fits. The short-run results are considered in the *Findings and Discussion* sections to support the arguments for policy recommendations based on long-run dynamics. The diagnostics test indicators suggest that all estimated models are free of serial correlation and heteroskedasticity problems. The adjusted-R^2 is a measure of accuracy for regression models. Table 5 shows that adjusted-R^2 for all the models was significant, indicating the model's goodness of fit. All error correction models were negative and statistically significant at the 5% level, consistent with the assumptions of the ARDL framework. The ECM represents the speed at which the system returns to equilibrium after a deviation in the long-run relationship, with its value expected to be greater than −2 and within the unit circle (Adeleye et al., 2018). Additionally, the results of the cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) tests for most models fell within the 5% significance boundaries, confirming the stability of the models (Xiong et al., 2023).

The estimated Granger causality results given in Table 6 indicate that GHG emissions demonstrate bidirectional causalities with EFP, ER, ET, PGDP, REG, and TTP. However, EPC, R&D, TMP, LFP, and FP establish unidirectional causalities with GHG emissions. PM2.5 bidirectional Granger causes EPC, ER, and REG. In addition, TMP, LFP, FP, and TTP unidirectionally cause PM2.5. Similarly, PM10 is bidirectional, causing EPC and REG; however, TMP, LFP, FP, and TTP unidirectionally cause PM10. The ecological footprint bidirectionally causes GHG, ER, PGDP, REG, and TTP. Likewise, EPC, ET, R&D, TMP, LFP, and FP unidirectionally cause EFP. Further details on EPC, ER, ET, and REG causalities are given in Table 6.

Findings and discussion

In this study, we examine the interaction among environmental policies, technological innovations, and renewable energy adoption to enhance environmental efficiency in the textile and fashion industry. Our findings demonstrate that stringent environmental regulations and taxes effectively drive the sector toward sustainable practices by significantly improving environmental performance. Although technological advancements are vital for long-term sustainability, our research shows that ET and research and development (R&D) impact different pollutants and may initially increase the ecological footprint due to high upfront costs and adjustments. Conversely, transitioning to renewable energy sources is crucial for significantly reducing the industry's carbon footprint. The LFP and FP sectors demonstrate greater responsiveness to environmental policies and regulations than other sectors, underscoring the significant influence of policy

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TABLE 6 Granger causality.

Variable	GHG	PM2.5	PM10	EFP	EPC	ER	ET	PDGP	REG	R&D	TMP	LFP	FP	TTP
GHG		3.56***	2.262***	3.76**		3.86*	2.23***	3.48***	6.76*					3.96**
PM2.5					2.21*	2.82***		4.68*	7.63*					
PM10					1.73***				5.83**					
EFP	2.81***				4.49**	2.77**		14.43*	4.89**					3.85***
EPC	4.34**	3.65*	2.53**	4.49**					2.98***			3.32***		6.93*
ER	24.14*	11.49*	8.98*	10.72*	2.97***		10.06*	6.23*			2.36**	7.18*	2.98***	6.03**
ET	3.79*			8.32*	4.27**	4.41*		4.78*	4.96**	3.76*				9.96*
PGDP	3.56**			6.37*	3.88***	3.49*	3.84*		5.97*	5.22*				6.11**
REG	3.99**	11.31*	9.01*	3.09***	3.24***		2.74**	3.62*		2.20***		2.87***		
R&D	5.96*			7.58*	4.21**	13.17*	3.02**	13.87*	5.28*			3.31***		10.66*
TMP	10.16*	14.04*	11.78*	7.48*			2.39**	2.02***	10.38*					3.96**
LFP	7.69*	10.92*	8.45*	6.18**	2.67***		2.34***	2.93**	3.62***					4.55**
FP	8.48*	11.09*	8.54*	6.41**			3.31**	3.01*	6.86*					3.36**
TTP	2.25***	4.04**	2.78***	4.02**	4.16**									

Note: *, **, and *** denote the significance level at 1%, 5%, and 10%, respectively. The same color shows bidirectional causality between variables.

implementation in these areas. This observation highlights the effectiveness and prioritization of environmental regulations within these sectors, reflecting a strategic emphasis on the reducing environmental impact through well-targeted policy measures. These findings provide a clear and actionable strategy, illustrating how an integrated regulatory framework, innovative technologies, and renewable energy can lead to a more sustainable and environmentally responsible textile industry. The contextual insights provided by this study are highly relevant to China's current environmental and industrial landscape. The findings reflect the dynamic interplay among policy, technology, and industry practices, offering practical recommendations for improving environmental efficiency. The research also contributes to the broader discourse on sustainable development by providing evidence-based insights into how different factors influence environmental performance in the textile and fashion industry (Li et al., 2021; Wang and Yu, 2021).

The use of taxes as a regulatory mechanism to mitigate the textile industry's environmental impact has gained increasing importance, particularly in China, where the sector is a significant contributor to pollution (DFU, 2023; Yu and Cheng, 2021). This study demonstrates that environmental policies and taxes effectively reduce GHG emissions and particulate matter (PM2.5 and PM10) across textile and fashion sectors (TMP, LFP, FP, and TTP). While EPCs significantly influence TTP, their broader impact is limited, suggesting that EPCs are more effective at the aggregate production level. In contrast, environmental taxes exhibit greater efficacy across all sectors, highlighting their superiority in curbing GHG emissions and air pollutants. The Granger causality analysis (Table 6) further confirms that both ERs and EPCs are causally linked to reductions in GHG, PM2.5, PM10, and ecological footprints, emphasizing the effectiveness of an integrated regulatory framework. These findings are in line with those obtained by He et al. (2021), suggesting that environmental taxes and policies are instrumental in reducing GHG emissions and air pollutants. Taxes are strict regulatory instruments; therefore, this study is in line with that by Shen et al. (2020), who suggested that command-and-control-type environmental policy tools positively affect green production.

China's regulatory framework for environmental protection has evolved significantly since the 1979 Environmental Protection Law. For instance, the Circular Economy Promotion Law (2009) mandates efficient resource use and waste reduction across industries, including textiles (Chen et al., 2021). The Cleaner Production Promotion Law (2003, revised 2012) builds on this foundation by mandating cleaner production audits, reducing toxic substance usage, and improving resource efficiency (Xu et al., 2024). The cornerstone of China's environmental governance is the Environmental Protection Law (revised 2014), which imposes stringent penalties for non-compliance and strengthens the authority of environmental protection agencies. This law has led to stricter pollution controls and increased accountability within the textile industry; however, enforcement challenges persist, particularly in economically dependent regions (Zhang et al., 2017).

The introduction of the Environmental Protection Tax Law (2018) marked a significant shift from pollution fees to a structured tax system, targeting air and water pollutants, solid waste, and noise emissions (Gao et al., 2022). China's FYPs further reinforce these regulatory efforts. The 13th FYP (2016–2020) made strides in reducing the energy intensity of the textile industry and promoting cleaner technologies. The 14th FYP (2021–2025) continues this trajectory with a heightened focus on green transformation and technological innovation. The 15th Five-Year Plan (2025–2030) emphasizes China's commitment to achieving its carbon neutrality goals. This plan focuses on advancing the nation's efforts toward zero-carbon emissions by 2060, promoting carbon neutrality, and further integrating green transformation and technological innovation across industries. The 15th FYP also prioritizes developing and implementing sustainable practices and technologies to accelerate the transition to a low-carbon economy. Despite these advances, challenges remain in achieving consistent implementation and target goals. Bidirectional causality among GHG emissions, PM2.5, PM10, EFP, environmental policies, technological advancements, and renewable energy transitions is revealed in this study, highlighting a complex, reciprocal relationship. In this study, we reveal that TMP, LFP, FP, and TTP exhibit unidirectional causality with GHG emissions, PM2.5, PM10, and EFP, indicating that these sectors respond to environmental policies, taxes, and technological changes.

The higher coefficient of REG indicates that it is the more efficient path for mitigating the GHG emissions, air pollutants, and ecological footprint in the textile and fashion industry. This study's findings also underscore the pivotal role of renewable energy adoption in reducing the industry's carbon footprint. The shift to renewable energy sources is vital for achieving significant long-term reductions in GHG emissions, supporting the theories of sustainable development and industrial ecology (Berg et al., 2019). By minimizing reliance on fossil fuels and optimizing resource use, renewable energy integration aligns with the principles of closed-loop systems and resource optimization advocated by industrial ecology (Chen et al., 2021). The findings support the notion that technological advancements and renewable energy adoption are critical for achieving higher levels of environmental efficiency, consistent with the conclusions obtained by Liu et al. (2019) and Yang et al. (2023). The Cleaner Production Promotion Law has driven significant improvements in waste management and energy efficiency within the textile sector; however, its effectiveness is contingent on consistent local enforcement (Xu et al., 2024). In addition, the Environmental Protection Tax Law (2018) incentivizes the adoption of pollution control technologies and more sustainable practices within the textile industry and mitigates GHG emissions by 41% and PM by 39% (Gao et al., 2022).

Environmental technologies and R&D have significant positive impacts on GHG emissions and environmental pollutants. However, ET and R&D only establish a causal relationship between GHG emissions and EFP (see Table 6). Interestingly, ET and R&D unidirectionally cause EPC and bidirectionally cause ER and REG. This study's findings contradict those obtained by Ghazouani et al. (2021) and Fernández et al. (2018), who suggested that ET and R&D significantly reduce GHG emissions in European countries. These findings indicate that investments in these areas are effective tools for environmental improvement. The unidirectional causality among ET, R&D, and EPC suggests that advancements in technology and R&D drive the development and implementation of stricter environmental policies. This implies that as new technologies emerge and R&D efforts advance, they create the groundwork for more stringent regulatory frameworks, likely because policymakers see the potential of these technologies to mitigate environmental impact effectively. The bidirectional causality among ET, R&D, ER, and REG indicates a dynamic interplay, where regulatory frameworks influence technological advancements. This mutual relationship suggests that as environmental regulations become more stringent, they push for further innovation in ET and R&D and the adoption of REG. Simultaneously, as new technologies and R&D outcomes become available, they encourage the evolution of more refined and targeted regulations. These findings underscore the critical role of ET, R&D, and renewable energy in shaping and being shaped by environmental policies and regulations. They reveal a feedback loop where technological progress and renewable energy adoption foster regulatory advancements, which, in turn, stimulate further innovation and adoption, creating a reinforcing cycle of environmental improvement. This dynamic interplay is essential for achieving sustained reductions in GHG emissions and broader environmental pollutants.

Theoretical implications

The findings of this study offer significant theoretical implications for understanding the interaction among environmental regulation, technological innovation, and renewable energy adoption within the textile and fashion industry. The findings affirm the EKC hypothesis, demonstrating that economic development, coupled with stringent environmental regulations, can reduce environmental degradation over time (Minlah and Zhang, 2021; Zhang et al., 2022b). In the textile and fashion industry, where production processes are resource-intensive, the EKC model suggests that regulatory interventions and economic incentives can drive the sector toward more sustainable practices as it matures, particularly in rapidly developing economies like China (Ruggerio, 2021). However, the study's findings also suggest that the relationship among technological advancements, regulatory frameworks, and environmental outcomes is more complex than the EKC hypothesis alone might suggest. The unidirectional causality among ET, R&D, and EPC indicates that technological innovation and R&D efforts not only respond to but also shape the regulatory environment. As new environmental technologies emerge, they lay the groundwork for more stringent regulations, accelerating the industry's transition to sustainable practices (Fernández et al., 2018; Ghazouani et al., 2021). This points to a more interactive, co-evolutionary process where technological and regulatory advancements reinforce each other (He et al., 2021).

Moreover, the bidirectional causality among ET, R&D, ER, and REG adoption underscores the reciprocal nature of these relationships. Regulatory pressures can stimulate innovation in environmental technologies and renewable energy adoption, which then feed back into the regulatory process, leading to the refinement of environmental policies (Chen et al., 2021). This feedback loop is critical for driving sustained environmental improvements in the textile and fashion industry and suggests that policymakers must adopt a holistic approach to achieve lasting environmental benefits (Berg et al., 2019; Yang et al., 2023). The study challenges traditional linear economic development and environmental improvement models, proposing a more complex, dynamic interplay among regulation, technology, and sustainability. The regulatory push innovation hypothesis confirms that stringent environmental regulations are not merely constraints but act as catalysts for innovation. As companies in China's textile sector face increasing regulatory pressures, they are driven to adopt cleaner technologies, optimize processes, and enhance environmental performance, aligning with Porter's hypothesis that regulatory pressures can open new market opportunities (Bibi et al., 2024; Porter and Linde, 1995). This assumption affirms the role of regulation as an active force for technological change, which is crucial for achieving sustainability in industries characterized by resource-intensive production like textiles. Furthermore, the policy synergy and interaction assumption highlights the importance of a comprehensive and integrated policy approach. This assumption suggests that the combined effect of various policy tools—such as environmental regulations, renewable energy incentives, and carbon taxes—can amplify the overall impact on sustainability. Rather than operating independently, these policies reinforce one another, facilitating the adoption of green technologies and practices (Li et al., 2024). The interaction between regulatory mechanisms and technological advancements, as illustrated in the textile industry, underscores the need for a harmonized policy environment to drive significant and sustained environmental improvements.

The dynamic interaction assumption offers an additional theoretical contribution by elaborating on the relationship between economic growth and environmental regulation, building on the EKC hypothesis. This assumption posits that as economic development progresses, regulatory frameworks evolve and firms begin to shift toward cleaner technologies and more sustainable practices. In China's rapidly developing textile sector, this dynamic suggests that environmental regulations and innovation are not only reactive but they also evolve in tandem with the industry's economic maturation (Minlah and Zhang, 2021; Ruggerio, 2021). This model challenges the linear view of environmental improvement, suggesting that regulation and economic growth can support each other in driving long-term sustainability. Last, the globalization assumption broadens the scope of environmental performance by highlighting the influence of international pressures. The increasing global demand for sustainable products compels Chinese firms to align with international sustainability standards, thereby driving innovation and compliance with both domestic and foreign regulations (Baah et al., 2021). This assumption extends the notion of environmental globalization, suggesting that external consumer preferences and regulatory frameworks play a critical role in shaping the local regulatory landscape and accelerating industry-wide changes toward sustainability. These insights have profound implications for both academic research and policymaking, highlighting the necessity of adopting integrated and adaptive strategies that foster meaningful, long-term environmental improvements in the textile and fashion industries (Liu et al., 2019; Shen et al., 2020).

Practical implications

The findings of this study have significant practical implications for the textile and fashion industry, offering key insights for industry leaders, policymakers, and innovators to effectively navigate the interaction among environmental regulations, technological innovation, and renewable energy adoption. To remain competitive and meet increasing consumer and investor demands for sustainability, industry stakeholders must proactively integrate environmental technologies and renewable energy solutions into their operations. This approach not only ensures compliance with stringent regulations but also establishes companies as leaders in sustainable development. The study's findings emphasize that environmental regulations should be seen as a catalyst for innovation rather than a limitation. Stringent policies can drive R&D in cleaner technologies, creating a reciprocal relationship where technological advancements lead to more effective regulations. Companies investing in R&D for environmental technologies are likely to gain first-mover advantages, access new markets, and mitigate long-term operational risks associated with environmental compliance.

Additionally, the adoption of renewable energy is crucial for achieving sustainability in the textile and fashion industry. By incorporating renewable energy sources such as solar or wind power into production processes, companies can significantly reduce their carbon footprint and align with global decarbonization trends. This shift not only meets regulatory demands but also enhances brand reputation among environmentally conscious consumers. Moreover, renewable energy adoption can result in long-term cost savings, especially in regions with volatile energy prices or government incentives. Policymakers should design environmental regulations that promote innovation and best practices rather than solely imposing penalties for non-compliance. This could involve offering tax incentives, grants, or subsidies to companies investing in environmental technologies or renewable energy. Policies encouraging collaboration among the industry, academia, and government can further accelerate the development and adoption of new technologies, facilitating a more rapid transition to sustainable practices across the sector. Last, the textile and fashion industry's shift toward sustainability can serve as a model for other resource-intensive sectors. Demonstrating how environmental regulations can drive technological innovation and renewable energy adoption will showcase the potential for harmonizing economic growth with environmental sustainability. This approach benefits the industry and contributes to broader societal goals of reducing environmental degradation and combating climate change. Sustainability should be viewed not as an optional add-on but as a core component of long-term business strategy and regulatory frameworks.

Conclusion

In conclusion, in this study, we offer significant insights into the intricate relationship among environmental regulations, technological innovation, and renewable energy adoption within China's textile and fashion industry. Whereas the EKC hypothesis posits a straightforward, linear relationship between economic development and environmental improvement, our findings reveal a more complex dynamic. The analysis demonstrates that the relationship between environmental regulations and sustainability is not one-directional. Instead, there exists a bidirectional influence where regulatory frameworks and technological advancements mutually reinforce each other. As companies in the textile sector face increasingly stringent regulations, they are prompted to innovate, adopting cleaner technologies and enhancing environmental practices. This innovation, in turn, drives further regulatory refinement as governments respond to industry advancements by enacting more targeted and supportive policies. Therefore, the relationship between regulation and innovation is dynamic and interdependent, rather than merely reactive. In this study, we also emphasize the necessity of an integrated approach to sustainability. It is not sufficient for policies and innovations to exist in isolation; they must be harmonized to achieve significant and long-lasting improvements. The synergistic interaction of environmental regulations, technological innovation, and renewable energy adoption creates a cohesive framework that can drive substantial environmental benefits. This finding suggests that policymakers should craft regulations that not only enforce compliance but also encourage innovation, particularly in the areas of renewable energy and sustainable production technologies. By designing policy frameworks that incentivize firms to adopt green technologies and renewable energy solutions, governments can facilitate a smooth transition to more sustainable practices across the industry.

The practical implications of this research are profound. Industry leaders must begin to view environmental regulations not as obstacles but as catalysts for innovation and business growth. In an increasingly competitive global market, the ability to innovate in response to regulatory pressures can provide firms with a distinct competitive edge. Furthermore, aligning innovation efforts with global sustainability goals will not only enhance the environmental performance of the industry but also position it as a leader in the global shift toward sustainable production practices. In this study, we also underscore the importance of collaboration among industry stakeholders, regulatory bodies, and international organizations to create a cohesive approach to sustainability that can serve as a model for other sectors. Ultimately, this research highlights that the path to sustainability in the textile and fashion industry is multifaceted and requires a concerted effort from all involved parties. By integrating regulatory pressures, technological innovation, and renewable energy adoption, the industry can navigate the complexities of environmental sustainability and become a benchmark for other sectors striving to balance economic growth with environmental responsibility. This study contributes to the growing body of knowledge on sustainability, providing both theoretical and practical frameworks for achieving long-term environmental improvements in resource-intensive industries.

Limitations and future research directions

This study is not without its limitations. One significant limitation is that the analysis primarily relies on existing data, which, although comprehensive, may not fully capture the latest technological and regulatory innovations within the textile and fashion industry. As the industry continues to evolve rapidly, the data available for analysis may not reflect recent shifts in technological advancements or regulatory frameworks. Additionally, the study's focus on specific regional contexts—namely, China's textile and fashion industry—may limit the broader applicability of the findings to other geographic areas with differing regulatory environments and market conditions. The diversity of regulatory policies across countries and regions, as well as varying levels of technological adoption in various textile and fashion sectors, presents a challenge to generalizing the results to a global scale. Future research should address these limitations by incorporating longitudinal studies that track the evolution of technological and regulatory landscapes over time. Such studies would provide a richer understanding of how industry dynamics and environmental regulations evolve, especially as new technologies and policy frameworks emerge.

Furthermore, the study does not delve into the direct impact of specific policy changes, which represents another important gap in the analysis. The absence of specific policy intervention data limits the ability to assess the nuanced effects of particular regulatory measures on sustainability outcomes. Future research could significantly benefit from adopting advanced methodologies such as difference-in-differences (DID) to analyze the causal impact of policy changes. By isolating the effects of specific regulatory interventions, such research would provide valuable insights into how particular policies drive technological innovation and environmental performance. This approach could be instrumental in formulating more targeted and effective policies for enhancing sustainability in the textile and fashion industry, offering clearer guidance for policymakers seeking to optimize regulatory strategies. In addition, comparative analyses across different regions and industries would further expand the generalizability of the findings and offer a more comprehensive understanding of how various factors—such as market conditions, regulatory intensity, and technological capabilities—interact to influence sustainability outcomes. By comparing industries in different countries or regions, research workers could identify patterns of innovation and regulatory success, providing a broader perspective on what drives industry-wide sustainability.

Data availability statement

Publicly available datasets were analyzed in this study. All data are available online; the sources are provided in the manuscript.

Author contributions

SB: conceptualization, formal analysis, investigation, methodology, writing–original draft, writing–review and editing, data curation, validation, and visualization. AsK: conceptualization, formal analysis, methodology, writing–original draft, writing–review and editing, validation, and visualization. XF: data curation, funding acquisition, investigation, methodology, resources, visualization, and writing–review and editing. HJ: formal analysis, funding acquisition, project administration, supervision, and writing–review and editing. SH: data curation, formal analysis, methodology, software, validation, visualization, writing–original draft, and writing–review and editing. ArK: data curation, investigation, resources, validation, and writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary Material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2024.1496454/full#supplementary-material.

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