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Research on the Application of Ecological Dyeing and Finishing Technology in the Textile Industry Driven by Government Policies: A Comparative Study of Policy Effects between China and Europe

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Article

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ABSTRACT

The textile and leather industries are under increasing pressure to achieve sustainable development, addressing environmental impacts across the entire value chain, from agricultural methods for raw materials like cotton and wool to final fiber products. The wet processing stages, including the dyeing and finishing of yarns and woven fabrics, are critical areas for improvement. These chemical operations traditionally consume vast resources and use complex organic compounds, which pose significant environmental challenges. This paper provides a comparative policy analysis of the application of ecological dyeing and finishing technologies within the textile industry of China and the European Union (EU). The study examines the impact of these advanced processes on a range of materials, including natural fibers like cotton and wool, as well as synthetic fibers. It scrutinizes the distinct policy frameworks and their effect on the adoption of innovative textile technologies and associated machinery and equipment, such as supercritical carbon dioxide (sc-CO_2) dyeing and digital printing. The analysis reveals differing policy effectiveness on the broader goals of sustainable development within the textile industry, impacting everything from raw material processing to the final characteristics of fiber products. This research offers crucial insights for policymakers and industry stakeholders aiming to foster a green transition in global textile manufacturing.

KEYWORDS

textile industry, sustainable development, cotton, wool, textile technology

INTRODUCTION

The textile industry is a cornerstone of the global economy, providing employment to millions and generating substantial revenue [1]. However, its environmental footprint is a matter of growing concern. The industry is a major consumer of water and energy, and a significant source of chemical pollution and greenhouse gas emissions [2]. The dyeing and finishing sub-sector is particularly resource-intensive and polluting [3]. Traditional dyeing processes can require up to 150 L/kg of fabric and utilize a complex cocktail of chemicals—including dyes, salts, and fixing agents—many of which are hazardous and persist in the environment [4, 5]. The effluent from these processes, if not adequately treated, can cause severe water pollution, harming aquatic ecosystems and human health [6]. In response to these environmental challenges and mounting public pressure, governments worldwide are implementing policies to promote the adoption of more sustainable practices in the textile industry [7, 8]. This has spurred the development and application of ecological dyeing and finishing technologies, which aim to reduce water and energy consumption, minimize the use of harmful chemicals, and decrease waste generation [9, 10]. These technologies include, but are not limited to, waterless dyeing techniques like supercritical carbon dioxide (sc-CO_2) dyeing, digital printing, foam dyeing, and the use of natural dyes and enzymatic treatments [11, 12].

China and the European Union (EU) are two of the most significant players in the global textile and apparel market. China is the world's largest textile producer and exporter, while the EU is a major consumer market and a significant producer of high-value textiles [13, 14]. Both have recognized the urgent need for a green transition in their textile sectors and have put in place distinct policy frameworks to drive this change [15]. However, much of the existing literature either examines these regions' policies in isolation or focuses on specific technologies without deeply analyzing the causal link between differing policy philosophies and real-world technology adoption patterns. A specific gap exists in a direct comparative analysis that contrasts China's state-led approach with the EU's market-integrated model to understand how these distinct pathways influence the pace and nature of sustainable innovation. This paper aims to fill that gap. It presents a comparative study of the policy-driven application of ecological dyeing and finishing technologies in the Chinese and European textile industries. The research seeks to comprehensively analyze and compare the policy landscapes for promoting sustainable textile production in both regions. It will further investigate the adoption and application of key eco-friendly dyeing and finishing technologies, while also evaluating the effectiveness of these policies in terms of their environmental impact and economic implications for the textile industry. Finally, the study aims to identify the challenges and opportunities for the wider adoption of these technologies and suggest potential areas for Sino-European cooperation. By conducting this comparative analysis, this study seeks to provide a holistic understanding of how different policy approaches can influence technological and sustainable transformations in a critical industrial sector, offering valuable insights for policymakers, industry practitioners, and researchers engaged in promoting environmental sustainability.

POLICY FRAMEWORK FOR ECO-DYEING AND FINISHING: A COMPARATIVE OVERVIEW

The approaches taken by China and the EU to foster sustainability in the textile industry are reflective of their broader political and economic systems. China's strategy is largely characterized by top-down, state-led planning and regulation, whereas the EU employs a more market-based and multi-stakeholder approach, with a strong emphasis on consumer information and circular economy principles.

China's Policy Landscape

China's environmental policy for the textile industry has evolved from a focus on end-of-pipe pollution control to a more integrated approach that emphasizes cleaner production and green development. Key policy instruments include:

Five-Year Plans (FYPs): These are the cornerstone of China's economic and social planning. The 14th FYP (2021-2025) explicitly calls for the green transformation of key industries, including textiles. It sets targets for reducing energy and water intensity, and for controlling the emission of major pollutants. The plan encourages the development and application of green and low-carbon technologies and promotes the recycling of textile waste.

Environmental Protection Law and Standards: China's Environmental Protection Law, revised in 2015, grants greater powers to environmental authorities to penalize polluters. The government has also established increasingly stringent national and local emission standards for the textile dyeing and finishing industry (e.g., GB 4287-2012), which set limits for pollutants in wastewater, such as chemical oxygen demand (COD), biochemical oxygen demand (BOD), and color.

Environmental taxes and subsidies: The environmental protection tax law, effective from 2018, levies taxes on enterprises based on their pollutant emissions, creating a direct economic incentive for companies to reduce their environmental impact. The government also provides financial support, including subsidies and tax breaks, for companies that invest in green technologies and cleaner production processes.

"Made in China 2025" and industrial upgrading: This strategic plan aims to transform China from a manufacturing giant into a global high-tech manufacturing power. For the textile industry, this translates into a push for higher value-added, technologically advanced, and sustainable production.

The enforcement of these policies is primarily carried out by local environmental protection bureaus (EPBs), which have the authority to inspect facilities, impose fines, and even order the shutdown of non-compliant factories. However, challenges in consistent and stringent enforcement across all regions remain.

European Union's Policy Approach

The EU's policy framework for sustainable textiles is embedded within its broader environmental and industrial strategies, notably the European Green Deal and Circular Economy Action Plan. The key policy instruments include:

- EU strategy for sustainable and circular textiles: Adopted in 2022, this strategy outlines a comprehensive vision for the future of the EU textile industry. It aims to make textiles more durable, repairable, reusable, and recyclable. Key actions include setting ecodesign requirements, introducing a digital product passport, tackling greenwashing, and promoting circular business models.
- Ecodesign for sustainable products regulation (ESPR): This regulation, a cornerstone of the textile strategy, will set mandatory ecodesign requirements for textiles sold in the EU market. These requirements will cover aspects such as product durability, reusability, reparability, recycled fiber content, and the presence of hazardous chemicals.
- Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH): REACH is a comprehensive regulation that controls the use of chemical substances in the EU. It places restrictions on the use of many hazardous chemicals commonly found in textile dyeing and finishing, such as certain azo dyes, phthalates, and heavy metals. This directly pushes manufacturers to find safer alternatives.
- Industrial Emissions Directive (IED): The IED sets operational conditions for industrial installations, including large textile dyeing and finishing plants, based on the principle of best available techniques (BAT). The BAT reference document (BREF) for the textile industry provides guidance on minimizing pollution and resource consumption.
- EU ecolabel: This is a voluntary scheme that awards a label to products and services that meet high environmental standards throughout their life cycle. The EU Ecolabel for textiles has strict criteria regarding fiber sourcing, chemical use, water and energy consumption, and product quality.

- Extended producer responsibility (EPR): The EU is moving towards mandatory EPR schemes for textiles, which will make producers financially responsible for the end-of-life management of their products. This is expected to incentivize the design of more sustainable and recyclable textiles.

The EU's approach relies on a combination of binding regulations, economic incentives, and voluntary schemes, with a strong emphasis on creating a level playing field within the single market and empowering consumers to make sustainable choices. To clearly summarize and contrast these two distinct policy systems, Table 1 provides a comparative analysis across key dimensions such as their primary drivers, main instruments, and enforcement mechanisms.

Table 1. Comparative Analysis of Policy Frameworks for Sustainable Textiles in China and the EU

Feature	China	European Union
Primary Driver	State-led, top-down planning	Market-, consumer-, and regulation-driven
Overarching Strategy	14th Five-Year Plan for green transformation	EU Green Deal & Strategy for Sustainable Textiles
Emission Control	Strict national/local emission standards (e.g., GB 4287-2012)	Industrial Emissions Directive (IED) & BAT principles
Chemical Management	Regulated via emission standards and pollutant lists	REACH Regulation
Product Lifecycle Rules	"Made in China 2025" for industrial upgrading	Ecodesign for Sustainable Products Regulation (ESPR)
Economic Instruments	Environmental Protection Tax Law; Direct subsidies for green tech	Extended Producer Responsibility (EPR) schemes; Circular economy financing
Enforcement Body	Local Environmental Protection Bureaus (EPBs)	Member State market surveillance; ECHA for chemicals

APPLICATION OF ECO-DYEING AND FINISHING TECHNOLOGIES

The policy frameworks in both China and the EU are driving the adoption of a range of innovative, eco-friendly dyeing and finishing technologies. The pace and scale of adoption, however, vary depending on the specific technology, the economic context, and the policy drivers.

Key Eco-Friendly Technologies

- Supercritical CO_2 Dyeing: This waterless dyeing technology uses sc-CO_2 as a solvent for disperse dyes, primarily for polyester fabrics. It eliminates the need for water in the dyeing process, resulting in zero wastewater discharge. It also allows for the recovery and reuse of the CO_2 and any unfixed dye, making it a highly sustainable option.
- Digital printing: Digital textile printing, particularly inkjet printing, offers significant environmental benefits over traditional rotary screen printing. It dramatically reduces water and dye consumption, as the dye is applied directly to the fabric where needed. It also allows for greater design flexibility and shorter production runs.
- Enzymatic treatments (biofinishing): Enzymes are used in various finishing processes, such as biopolishing of cotton to reduce pilling, and for scouring and bleaching. They are biodegradable, operate under mild conditions (lower temperatures and neutral pH), and can replace harsh chemicals, thereby reducing water and energy consumption and producing less toxic effluent.
- Natural and biodegradable dyes: There is a growing interest in reviving the use of natural dyes derived from plants, minerals, and other organic sources. While scalability and color fastness can be challenges, research is ongoing to improve their performance. Additionally, new biodegradable synthetic dyes are being developed to reduce the environmental persistence of conventional dyes.
- Foam dyeing: This technology uses a foam medium to apply dyes to fabric, significantly reducing the amount of water required compared to conventional wet-processing methods.
- Plasma technology: Plasma treatment can be used to modify the surface of textile fibers, improving their dyeability and reducing the need for chemical pre-treatments. Table 2 offers a detailed comparison of the environmental benefits of these key technologies and analyzes their respective adoption drivers within the different policy contexts of China and the EU.

Table 2. Comparison of Environmental Benefits and Adoption Drivers for Key Eco-Dyeing and Finishing Technologies

Eco-Technology	Description & Key Environmental Benefit	Adoption Driver in China	Adoption Driver in EU
Supercritical CO_2 Dyeing	Waterless dyeing technique, zero wastewater discharge, energy saving	Meeting strict wastewater standards; government subsidies	Pursuit of cutting-edge sustainability; enhancing brand's

		for high-tech	eco-image
Digital Printing	On-demand inkjet application, significantly reducing water, dye, and chemical use	Demand for industrial upgrading; production flexibility for small batches and fast fashion	Meeting personalized customization demand; complying with Ecolabel criteria
Enzymatic Treatment	Using biological enzymes to replace harsh chemicals; mild process conditions, less toxic effluent	Cleaner production audit requirements; reducing overall production costs	REACH restrictions on hazardous chemicals; consumer preference for “biofriendly” products
Natural Dyes	Using dyes from natural sources like plants and minerals; good biodegradability	Meeting niche market demands; supplementing a company’s green image	Strong market pull; demand for organic and natural product certifications

Adoption in China

The Chinese government’s strong regulatory push and financial incentives have accelerated the adoption of certain eco-friendly technologies. The stringent enforcement of wastewater discharge standards has been a particularly powerful driver for the adoption of technologies that reduce water pollution.

- Water-saving and wastewater-treatment technologies: Many Chinese textile companies have invested heavily in advanced wastewater treatment facilities. There is also a growing adoption of low-liquor-ratio dyeing machines and other water-saving equipment.
- Adoption of cleaner production technologies: The promotion of cleaner production audits has encouraged companies to adopt technologies like enzymatic treatments and to optimize their production processes to reduce resource consumption.
- Challenges in adopting advanced technologies: The adoption of more capital-intensive and technologically advanced solutions like supercritical CO_2 dyeing is still limited to a smaller number of larger, more innovative companies due to the high initial investment costs. However, government support for technological innovation is helping to lower this barrier. To illustrate a direct policy-to-application link, consider the case of supercritical CO_2 dyeing. For a large polyester dyeing facility in a province with strictly enforced wastewater standards (like GB 4287-2012), the daily operational costs of treating vast amounts of effluent, coupled with the taxes levied on pollutant discharge under the Environmental Protection Tax Law, create a significant and ongoing financial burden. In this context, the

technology's primary benefit—zero wastewater discharge—transforms the high initial investment from a simple cost into a strategic solution for long-term penalty avoidance and operational stability. When combined with government subsidies for high-tech industrial upgrading, these specific regulatory pressures provide a direct and powerful financial incentive for companies to adopt such a capital-intensive, waterless technology.

- Case study insights: Case studies of Chinese textile mills reveal that while regulatory pressure is the primary driver for adopting sustainable practices, government subsidies and technical support programs play a crucial role in enabling these investments. For instance, some leading textile companies in provinces like Zhejiang and Jiangsu have become pioneers in adopting digital printing and automated dyeing systems, partly due to local government support for industrial upgrading.

Adoption in the EU

In the EU, the adoption of eco-friendly technologies is driven by a combination of stringent chemical regulations (REACH), consumer demand for sustainable products, and the branding and market access advantages offered by schemes like the EU Ecolabel.

- Focus on chemical substitution and safe materials: The REACH regulation has been a major catalyst for the substitution of hazardous chemicals with safer alternatives in dyeing and finishing processes. This has spurred innovation in green chemistry.
- Growth of digital printing: The EU has seen significant growth in digital textile printing, driven by the demand for fast fashion, customized products, and more sustainable production methods. Italy, in particular, is a leader in high-quality digital textile printing.
- Market pull for sustainable products: European consumers are increasingly aware of the environmental and social impacts of textiles. This has created a strong market pull for products with credible sustainability credentials, such as those made with organic cotton, recycled fibers, and dyed with certified low-impact dyes.
- Case study insights: European textile companies, especially those in the high-end market segments, often leverage sustainability as a key competitive advantage. Case studies show that many of these companies have proactively invested in technologies like water-saving dyeing machines and renewable energy sources, not only to comply with regulations but also to enhance their brand image and appeal to environmentally conscious consumers. For example, some Scandinavian and German textile brands

have been at the forefront of adopting circular economy models, including take-back schemes and the use of recycled materials.

COMPARATIVE ANALYSIS OF POLICY EFFECTIVENESS

A comparative analysis of the policy effectiveness in China and the EU reveals the strengths and weaknesses of their respective approaches. The effect pathways that have formed under these policy drivers show significant differences, and Figure 1 visually represents these two distinct models. While acknowledging overlaps exist in both systems, the "command-and-control" nature of China's regulations tends to foster a primarily compliance-driven adoption model. Conversely, the EU's market-integrated strategy generally encourages a more innovation-oriented approach, although regulatory compliance remains a fundamental baseline for all operators.

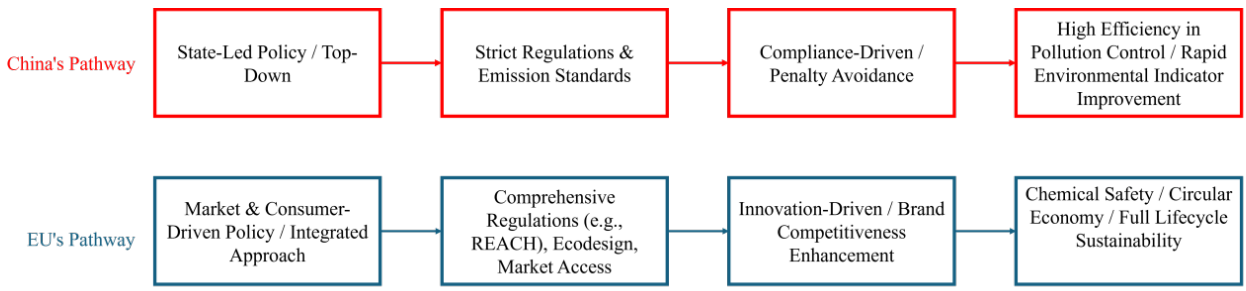

Figure 1. Conceptual Diagram of the Primary Policy-Driven Effect Pathways for Eco-Textiles in China and the EU

Drivers for Technology Adoption

China: Regulation-driven adoption

The primary driver for the adoption of eco-friendly technologies in China is "command-and-control" regulation. The fear of heavy fines, production suspensions, and factory closures is a powerful motivator for compliance. This approach has been effective in achieving rapid, large-scale improvements in basic environmental performance, particularly in wastewater treatment. This is not to say innovation is absent; for some leading firms, increasingly stringent regulations have acted as a powerful catalyst for developing proprietary green technologies, turning a regulatory burden into a market advantage.

EU: Market- and Value-Chain-Driven Adoption

In the EU, while regulation sets a clear baseline, market forces play a more significant role. The "pull" from brands and consumers for sustainable products, coupled with the stringent requirements of regulations such as REACH, creates a more innovation-oriented environment. Companies are incentivized to go beyond compliance to gain a competitive edge. Nevertheless, penalty avoidance remains a crucial underlying motivator. Non-compliance with foundational regulations like REACH or the IED carries significant financial and legal consequences, ensuring a baseline of regulatory adherence across the industry.

Environmental Impact

Both regions have seen positive environmental outcomes from their policies.

- China: China has made significant progress in tackling water pollution from the textile industry. The concentration of major pollutants in industrial wastewater has decreased markedly. However, challenges remain in areas such as sludge disposal, soil contamination, and greenhouse gas emissions.
- EU: The EU’s policies have been effective in reducing the use of hazardous chemicals and promoting the use of more sustainable materials. The focus on circularity is also beginning to address the issue of textile waste. However, the overall environmental footprint of textile consumption in the EU remains high, as a large proportion of textiles are imported from regions with less stringent environmental standards.

Direct quantitative comparisons of the environmental impact are challenging due to differences in data availability and reporting standards. However, to substantiate the analysis, illustrative data can be presented. For instance, China’s focus on pollution control is reflected in its industrial wastewater statistics. According to China’s National Bureau of Statistics, the national average chemical oxygen demand (COD) in wastewater from key industrial sectors saw a reduction of over 30% from 2015 to 2020. Conversely, the EU’s progress is more evident in circularity and chemical management metrics. The European Environment Agency reports that the collection rate for used textiles across the EU is approximately 25–30%, with the new EU Strategy for Sustainable and Circular Textiles aiming to drastically increase this figure by 2030. Furthermore, over 200 hazardous substances relevant to textiles have been restricted under REACH. These differing indicators support the conclusion that while both regions show positive trends, their policy priorities shape their areas of greatest improvement.

However, available data suggests that both regions are on a positive trajectory, albeit with different areas of focus and varying rates of improvement.

Economic Implications

The economic impacts of these policies on textile enterprises, particularly SMEs, are a critical aspect of the analysis.

- Investment costs and competitiveness: In both regions, the adoption of eco-friendly technologies requires significant upfront investment, which can be a major barrier for SMEs. In China, while government subsidies can alleviate some of this burden, the pressure to invest in pollution control equipment can strain the financial resources of smaller companies. In the EU, the costs of compliance with regulations like REACH can be substantial. There are concerns in both regions that these costs could undermine the international competitiveness of their textile industries.
- Economic benefits and opportunities: On the other hand, investing in sustainable technologies can lead to long-term economic benefits, such as reduced operational costs (from lower water, energy, and chemical consumption), improved resource efficiency, and enhanced brand reputation. In the EU, sustainability is increasingly seen as a source of innovation and a key differentiator in the global market. In China, companies that successfully upgrade their technologies and environmental performance are better positioned to thrive in a more regulated and competitive domestic market and to access international markets with high environmental standards.
- Impact on SMEs: While large corporations may have the resources to adapt, SMEs in both China and the EU face disproportionate challenges, which can be attributed to specific market failures and structural barriers. Structurally, SMEs often lack the economies of scale, possess limited access to capital markets for financing high-cost eco-innovations, and have less bargaining power with technology suppliers. In terms of market failures, they lack dedicated R&D personnel to evaluate the complex array of new technologies and to accurately forecast their return on investment. In China, a key structural barrier for SMEs is the rapid, top-down enforcement of regulations, which can demand immediate compliance investments that exhaust their limited capital. In the EU, SMEs may struggle more with the administrative burden of navigating complex regulations like REACH and meeting extensive documentation requirements for certifications like the EU Ecolabel. Therefore, policy support must move beyond generic "financial assistance" and "technical guidance." More effective mechanisms could include: in China, creating state-sponsored regional centers for green technology rental or sharing to lower upfront costs; in the EU, establishing simplified compliance pathways for SMEs within regulations like ESPR. For both

regions, government-backed green credit programs with lower interest rates, and university-SME partnerships to bridge the information gap, would be crucial for fostering a more just and inclusive green transition.

DISCUSSION

The comparative analysis highlights that there is no one-size-fits-all policy approach to promoting sustainable technology adoption, as the effectiveness of any policy is deeply contingent on the specific economic, social, and political context of its implementation. Interpreting the findings, China's state-led, regulation-heavy approach has been instrumental in forcing a rapid and widespread baseline improvement in the environmental performance of its massive textile industry. This "shock therapy" was arguably necessary to address the severe pollution problems resulting from decades of rapid, unchecked industrial growth. The EU's more gradual, market-integrated approach, on the other hand, appears to be more effective in fostering deeper, more systemic innovation and in embedding sustainability into the core business strategies of companies. These differing approaches naturally lead to unique challenges and opportunities for both regions. A key challenge for China is to evolve from a culture of mere compliance towards one of proactive environmental innovation. For the EU, a major challenge is to address the environmental impact of its consumption, which is largely externalized to other parts of the world, raising complex issues of global supply chain responsibility. Opportunities, however, lie in the potential convergence of these policy approaches, as China is increasingly incorporating market-based instruments into its policy mix, while the EU strengthens its regulatory framework with measures like the ESPR. While the differing policy philosophies present challenges to cooperation, they also create opportunities for synergy if approached pragmatically. Rather than a wholesale policy merger, cooperation could focus on specific, mechanism-based initiatives. For example, a joint working group could focus on harmonizing technical standards for specific eco-technologies like waterless dyeing, creating a common benchmark that satisfies China's focus on pollution metrics and the EU's interest in verifiable green claims. Another concrete mechanism would be to establish pilot projects for a shared supply chain data-tracking system, which would help Chinese manufacturers meet the upcoming requirements of the EU's Digital Product Passport. However, the limitations are significant. The EU may perceive China's state subsidies for green technology as an unfair trade practice, while China may view the EU's Ecodesign requirements as a green trade barrier. Overcoming these political-economic frictions would require a dedicated diplomatic track that runs parallel to any technical collaboration, focusing on mutual recognition rather than full alignment.

CONCLUSION

The transition to a sustainable and circular textile industry is a global imperative, and this study has provided a comparative analysis of the policy-driven application of ecological dyeing and finishing technologies in China and the EU. The findings demonstrate that both regions have implemented ambitious policy frameworks that are successfully driving the adoption of cleaner technologies and practices. China's top-down regulatory approach has been effective in achieving rapid improvements in environmental performance, particularly in pollution control, while the EU's market-oriented and consumer-focused strategy has fostered innovation and embedded sustainability as a competitive advantage. However, both approaches have their limitations and face ongoing challenges. The key policy implication from this analysis is that a "one-size-fits-all" approach is ineffective; instead, policymakers can learn from the transferable "best practices" of each region, provided they consider their own specific context. For instance, China's model of setting stringent, non-negotiable environmental standards (e.g., for wastewater) is a highly transferable practice for developing economies grappling with severe industrial pollution, where rapid baseline improvements are a priority. This approach, however, requires a strong central regulatory capacity for effective enforcement. Conversely, the EU's Ecodesign principle, which holds producers responsible for a product's entire lifecycle, is a powerful best practice for mature markets aiming to foster innovation and address consumption-driven environmental impacts. Its successful transfer requires high consumer awareness and the institutional framework to manage complex information systems like the Digital Product Passport. Future research should focus on developing hybrid policy models that sequence these approaches—perhaps starting with strict pollution control and evolving towards more sophisticated lifecycle and circular economy frameworks. Future research should therefore focus on more detailed quantitative comparisons of specific policy instruments and on in-depth case studies of the economic and social impacts of this green transition. As China and the EU continue to advance their green agendas, there is a significant opportunity for them to work together to lead the global textile industry towards a more sustainable and prosperous future, and the choices they make will have a profound impact not only on their own economies and environments but also on the planet as a whole.

Availability of Data and Materials

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

Author Contributions

Jiyuan Ma designed, collected and analyzed the data, and drafted the manuscript. Jiyuan Ma conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Jiyuan Ma participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Conflict of Interest

The author declares no conflict of interest.

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