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Greenhouse Gas Emissions and Mitigation Strategies for Synthetic Textile Dyeing and Finishing Sector

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Abstract: China, as the world's largest producer and consumer of synthetic textiles, faces sustainability challenges in the synthetic textile dyeing and finishing sector. The greenhouse gas (GHG) emission profiles and potential mitigation pathways for this sector require further classification. This study analyzed the GHG emissions from the synthetic textile dyeing and finishing process of eight representative life cycle assessment (LCA) cases. To explore the potential for emission mitigation, four mitigation strategies were developed, resulting in the formulation of 11 scenarios. The average GHG emissions per kilogram of synthetic textiles from the dyeing and finishing process were 3.06 kg CO_2 equivalent (eq) (ranging from 1.83 to 5.34 kg CO_2 eq), primarily contributed by the dyeing unit and resulting from energy consumption (steam and electricity). The scenario analysis suggested that in the business-as-usual scenario, GHG emissions from the dyeing and finishing sector could reach 17.79 Mt CO_2 eq by the year of 2060. Emission mitigation potentials across scenarios ranged from 35.72% to 71.65%. In the most optimistic scenario, emissions could be reduced to as low as 5.04 Mt CO_2 eq by the year of 2060. These findings provide valuable insights to identify key mitigation pathways for the synthetic textile dyeing and finishing sector.

Keywords: dyeing and finishing; life cycle assessment (LCA); synthetic textile; greenhouse gas (GHG) emission

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0 Introduction

The textile industry has become a pillar of the global economy, yet it has not moved beyond a model characterized by low efficiency, high resource consumption, and high pollution[1-3].

Being the second largest pollution industry worldwide, the textile sector emits 17 t of greenhouse gas (GHG) and 160 t of wastewater for every ton of textiles produced[4-6], with emissions intensified in coal-dependent manufacturing hubs[7]. Given the significant environmental impact, it is imperative to address the sustainability of the textile industry, particularly in the areas of GHG emissions and resource management. GHG emissions occur throughout the entire textile industry chain, and the dyeing and finishing sector notably stands out as a substantial contributor[8]. Studies on the global garment value chain also emphasized the significance of the dyeing and finishing sector, attributing 36% climate impact and 24% freshwater use[9]. In the context of increasing demand for textiles[10], it is necessary and urgent to quantitatively measure the GHG emissions of the dyeing and finishing process to put forward mitigation strategies for textile production.

The dyeing and finishing process has resulted in GHG emissions, fossil resource scarcity, freshwater eutrophication, eco-toxicity, and human toxicity[11-12]. Increasing studies have focused on the water footprint of the dyeing and finishing sector[13]. These investigations indicate that processing 1 t of product in the dyeing plant generates 91 m^3 of wastewater, 160 kg chemical oxygen demand (COD), and a water alkalization footprint of 15.478 kg of OH^- equivalent (eq)[14-15]. The GHG emissions from the dyeing and finishing sector contribute to climate change and are facing increasingly stringent regulatory scrutiny within the textile industry, making this situation an issue that cannot be ignored. The synthetic textile dyeing and finishing sector suffers from

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low data transparency and varying GHG emissions across products[16]. This study selected representative products as an entry point to investigate the general GHG emission characteristics of the dyeing and finishing process, identified key optimization factors, and proposed targeted mitigation strategies.

Life cycle assessment (LCA) has been implemented in evaluating the environmental impacts of the textile industry[17], which is a standardized and systematic method to characterize the environmental performance of a specific product[18-19]. By using the cradle-to-grave LCA, Luo et al.[20] indicated that the manufacturing of a pair of cotton jeans consumed 13.74 m^3 of water and emitted 90.37 kg CO_2 eq. Kazan et al.[21] evaluated the environmental impact of manufacturing a cotton T-shirt, taking into account different production scenarios. The findings demonstrated that substituting conventional methods with organic cotton cultivation and renewable energy sources resulted in a reduction of eutrophication potential, acidification potential and global warming potential by 48%, 52% and 70%, respectively. Gomez-Campos et al.[22] established a comprehensive life cycle inventory (LCI) from flax cultivation to flax technical textiles and evaluated the environmental impacts at different stages. However, the aforementioned research primarily focused on GHG emissions of natural textiles across the whole production process, especially for cotton. Although synthetic fibers contribute 62.2% of the global fiber production[23], there is a lack of in-depth analysis of them. Additionally, GHG emissions of the dyeing and finishing sector, treated as a black-box, have not been well-documented in textiles production. For example, Wang et al.[24] evaluated the carbon footprint of a pure cotton shirt (8.771 kg CO_2 eq) from the cotton production to the product use stage, where the production process caused more than 50% of the emissions. Fidan et al.[25] assessed the global warming potential of a pair of jeans by combining spinning, rope dyeing, weaving, and finishing into a textile production unit, but no in-depth analysis of the dyeing and finishing process was provided. China, as the world's largest producer and consumer of synthetic textiles, possesses a complete textile production chain. The comprehensive infrastructure allows for an accurate evaluation of the GHG emissions associated with the dyeing and finishing sector of synthetic textiles.

While existing studies have laid a solid foundation for analyzing the sector's GHG mitigation potential, such as the cement[26], chemical[27], and transport sectors[28], there is a lack of a comprehensive analysis of GHG mitigation potential in the synthetic textile dyeing and finishing sector. For example, Talaei et al.[29] employed bottom-up energy modeling and scenario analysis to assess long-term GHG mitigation potential in the cement industry. The net present value, cost of saved energy, and GHG emissions were calculated to evaluate the economic performance of different scenarios. Espinosa Valderrama et al.[30] estimated GHG emissions produced by the Colombian transport sector. Their analysis showed that the proposed measure could achieve a GHG mitigation of 8% by 2030 and 18% by 2050 under the business-as-usual scenario, although the mitigation cost was high. The textile sector, particularly dyeing and finishing, needs similar attention to quantify GHG emission trends, evaluate effective mitigation strategies, and support global climate goals.

To bridge these gaps, this study conducted a gate-to-gate LCA analysis on colored synthetic textiles based on process subdivision in China. The objectives were to analyze the general characteristics of GHG emissions from the synthetic textile dyeing and finishing sector, identify the key sources and factors contributing to GHG emissions among sub-processes, and evaluate the GHG mitigation potential of different strategies in this sector. The results are expected to provide effective low-carbon pathways and policy implementation support for decision-makers.

1 Materials and Methods

1.1 LCA method

1.1.1 Goal and scope definition

The synthetic textile dyeing and finishing sector is a crucial segment of the textile industry. In China, airflow dyeing and overflow dyeing are the most commonly used methods for synthetic textiles. To gain insights into the general characteristics of the dyeing and finishing process, we conducted a field study in Jiangsu, a major industrial agglomeration province for the dyeing and finishing sector in China, in 2022. A representative enterprise was selected, and the dyeing and finishing process of eight typical synthetic textile products (denoted as P1, P2, …, and P8) was tracked to ensure the study's representativeness and comprehensiveness. The specific case product information and the main process flow are depicted in Table 1 and Fig. 1.

Table 1 Specific case product information

Product	Dyeing method	Liquor ratio	Material
P1	Overflow dyeing	17.16 : 1	Polyamide
P2	Overflow dyeing	14.10 : 1	Polyester/cotton
P3	Overflow dyeing	11.81 : 1	Polyester
P4	Overflow dyeing	10.34 : 1	Polyamide
P5	Airflow dyeing	10.32 : 1	Polyester/polyamide
P6	Airflow dyeing	8.38 : 1	Polyester
P7	Airflow dyeing	7.89 : 1	Polyamide
P8	Overflow dyeing	5.99 : 1	Polyester

The process-based LCA method was adopted, using 1 kg of the colored synthetic textiles as the function unit (FU). The system boundary was set from gate to gate, covering the pretreatment, dyeing, finishing, and wastewater treatment (WWT) units (Fig. 2). Notably, stitching, setting stitching, and drying processes were excluded from the system boundary due to insufficient information. They only involved little electricity consumption and had minimal impact on the overall results.

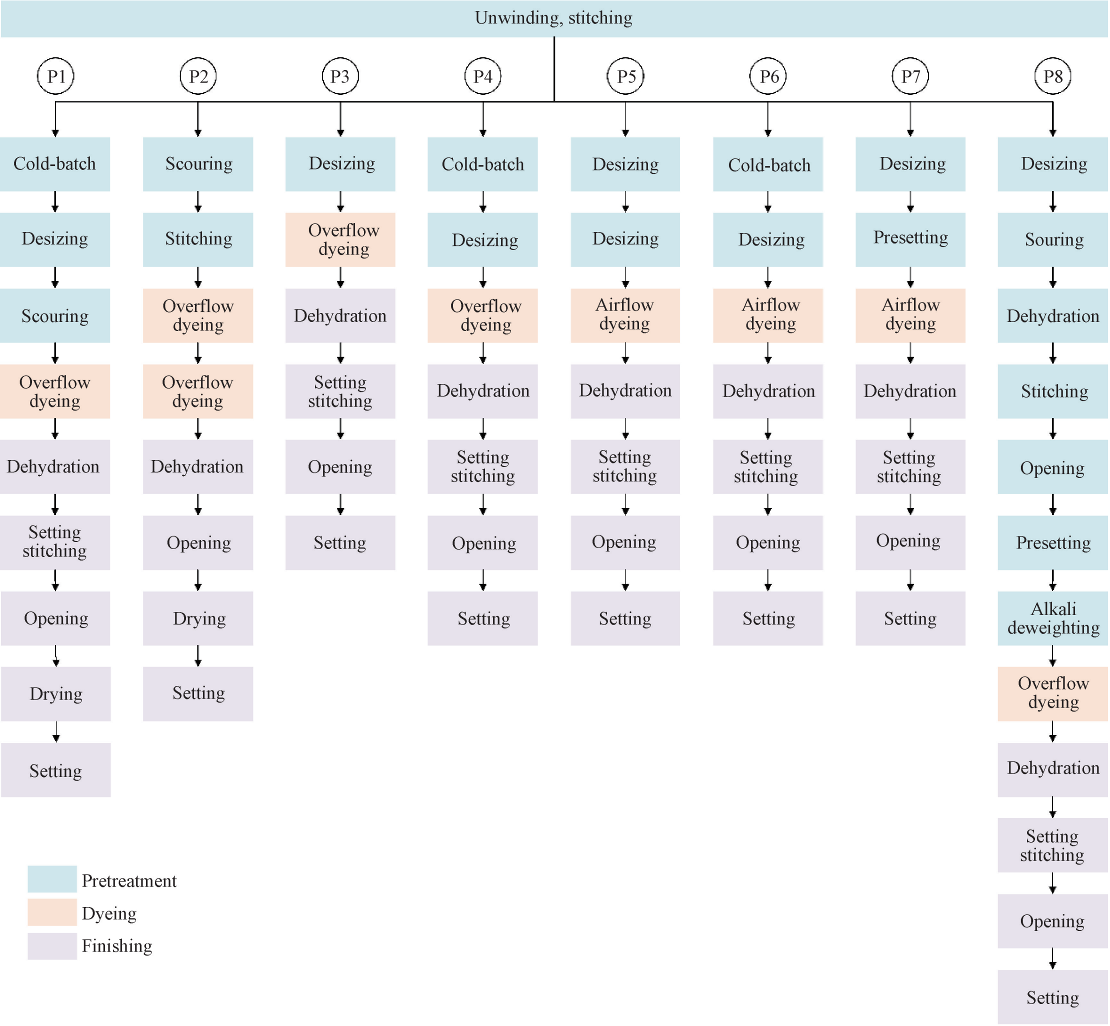


Fig. 1 Flow diagram of eight products' dyeing and finishing process

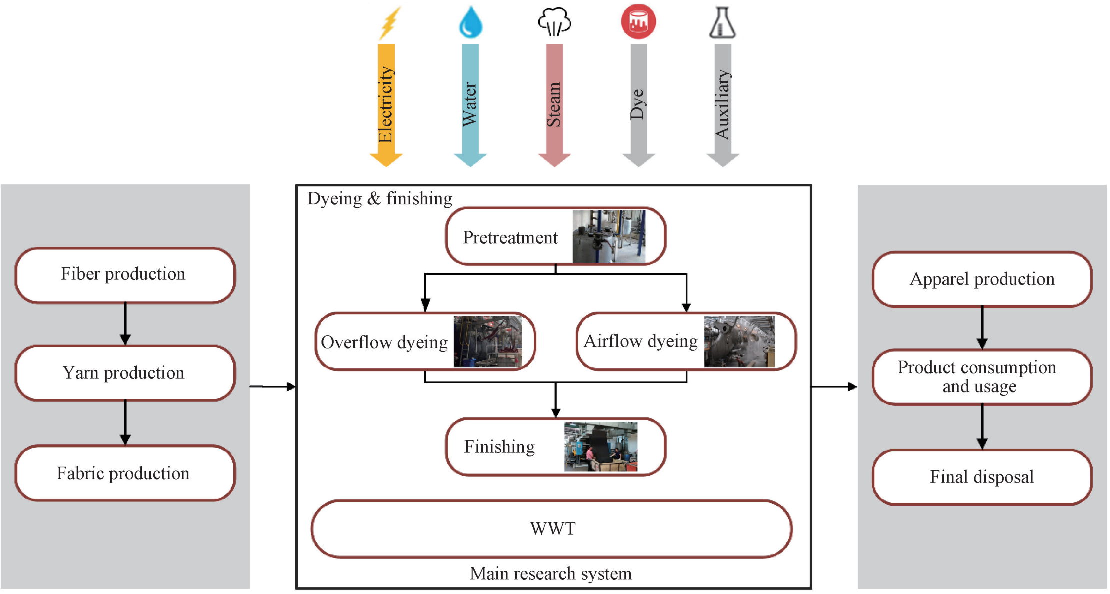


Fig. 2 System boundary in this study

1.1.2 LCI

This step collected data on the energy, material, and emissions associated with each sub-process. The data collection for electricity, steam, and water was based on Ⅲ-level measurement data (energy consumption data for each piece of equipment, such as the desizing machine, dyeing machine, and setting machine). A follow-up interview confirmed steam usage, revealing that medium-pressure steam (1 – 4 MPa) was utilized in the setting phase, while low-pressure steam (< 1 MPa) was employed in the other phases. Material data were sourced from the process cards of each product line. Emission data were calculated by using the concentration of wastewater pollutants[31] and the volume of wastewater generated. Since all wastewater in the dyeing and finishing plant is collected and treated uniformly, it is impossible to distinguish the wastewater volume from each processing line. Therefore, it is assumed that the wastewater volume of each sub-process is equal to its water usage. The background data, including the electricity, chemicals, and other materials used in this study, were obtained from the Sphera database. In addition, direct CH_4 emissions in the WWT process are calculated by

$$E = \sum E_i, \tag{1}$$

$$E_i = R_i \times B \times M, \tag{2}$$

$$R_i = C_i \times \eta_i, \tag{3}$$

where E represents the CH_4 emissions in the WWT process per FU (kg CO_2 eq); E_i refers to the CH_4 emissions in the WWT process from the ith process (kg CO_2 eq); R_i denotes the amount of COD removed in the WWT process from the ith process (kg); B is the CH_4 emission potential factor of anaerobic WWT systems (0.25 kg CH_4/kg COD[32]); M is the CH_4 correction factor (0.3 with no unit[32]); C_i represents the amount of COD of the wastewater generated from the ith process (kg); η_i is the average COD removal efficiency of the wastewater generated from the ith process. The value η_i can be obtained from the manual of emission coefficients for the Second National Pollution Source Census[31].

1.1.3 Impact assessment

The LCA for Expert (Version 10.7) was utilized to construct the LCA models. Climate change impacts were assessed by using a 100-year timeframe. This approach serves as a valuable indicator for quantifying life cycle GHG emissions from recent decades[33] and enables comparisons with previous relevant studies. For this assessment, the global warming potential (GWP) follows the guidance of the IPCC AR6[34], which employs the latest CO_2 equivalence metrics.

1.2 Sensitivity analysis

Sensitivity analysis was conducted to identify the key factors affecting GHG emissions. Based on the results of the LCI, a 10% change was applied to each major input parameter with all other factors unchanged, to examine the sensitivity of GHG emissions in response to changes in inputs.

1.3 Scenarios development for GHG mitigation potential

In 2022, China's total production of colored synthetic textiles reached 15.02 billion meters[35-36]. The national production of colored synthetic textiles has exhibited a growth trajectory, with a compound annual growth rate of 1.30% from 2015 to 2022[37]. Following this trend, it is anticipated that the production of colored synthetic textiles will continue to rise, resulting in heightened GHG emissions in the future.

To assess the GHG mitigation potential in the synthetic textile dyeing and finishing sector, scenarios were developed spanning the period from 2023 to 2060. Several key parameters, such as electricity structure, steam source, technology penetration, and industry scale, were considered due to their significant impact on GHG emissions. Electricity and steam are the primary contributors to GHG emissions, as the energy system in China is heavily reliant on coal. Therefore, optimizing the electricity mix and steam source can substantially reduce GHG emissions. Technology penetration considers not only the ongoing transition from overflow dyeing to airflow dyeing but also the adoption of supercritical fluid dyeing (SFD). Although SFD has not yet been industrialized in China due to high equipment investment costs and the immaturity of this technology[38], its environmental benefits (such as zero wastewater discharge and energy consumption at 80% of that in the traditional process) offer significant potential for future applications. The industry scale is represented by the compound annual growth rate. As shown in Tables 2 and 3, the key parameters are set based on the current industry development status, relevant policies[39], and the "14th Five-Year Plan" for the development guidance of the dyeing and finishing sector[40]. The "low" represents a linear change of the parameter from the level in 2022 to the low-carbon development level by 2060. The "medium" reflects a linear shift of the parameter from the level in 2022 to the advanced level by 2060. The "high" assumes that the parameter remains at the level in 2022 without change.

Table 2 Parameters of industry scale and technology penetration setting

Level	Industry scale in 2060/%	Technology penetration in 2060/%		
		Overflow dyeing	Airflow dyeing	SFD
High	1.30	78.00	22.00	0
Medium	0.50	40.00	40.00	20.00
Low	0.25	30.00	40.00	30.00

Table 3 Parameters of electricity mix and steam source setting

Level	Electricity mix in 2060/%							Steam source in 2060/%		
	Coal	Natural gas	Oil	Water	Nuclear	Wind	Solar	Coal	Natural gas	Biomass
High	62. 95	3. 58	0. 02	15. 28	4. 72	8. 62	4. 83	100. 00	0	0
Medium	15. 00	15. 00	0	10. 00	5. 00	15. 00	40. 00	20. 00	40. 00	40. 00
Low	5. 00	5. 00	0	15. 00	10. 00	20. 00	45. 00	0	50. 00	50. 00

According to the values of the parameters, we set 11 scenarios (Table 4), which can be divided into four categories. Each scenario represents a potential pathway for GHG mitigation. The current policy scenario incorporates medium-level parameters and represents the most plausible scenario attainable within existing policy frameworks. Based on the current policy scenario, we developed various scenarios, including single-parameter scenarios and combined-parameter scenarios. The latter included a most optimistic scenario and a business-as-usual scenario, both formulated by adjusting multiple parameters. When a single parameter is set to its maximum and minimum values, these two settings correspond to the scenarios with the highest and lowest GHG emissions, respectively. Together, they define the range of the parameter's impact on sectoral GHG emissions. These two scenarios also define the maximum possible range of impact. The GHG mitigation potential of each parameter is quantified by the ratio between the two ranges, illustrating the magnitude of its influence on emission mitigation.

Table 4 Scenario setting

Scenario	Scenario code	Meaning of scenario	Parameter			
			Industry scale (I)	Technology penetration (T)	Electricity mix (E)	Steam source (S)
Current policy	CP	Most likely scenario under the current policy	Medium	Medium	Medium	Medium
Single-parameter	LI	Low emission scenario with adjustment of the industry scale	Low	Medium	Medium	Medium
	HI	High emission scenario with adjustment of the industry scale	High	Medium	Medium	Medium
	LT	Low emission scenario with adjustment of technology penetration	Medium	Low	Medium	Medium
	HT	High emission scenario with adjustment of technology penetration	Medium	High	Medium	Medium
	LE	Low emission scenario with adjustment of the electricity mix	Medium	Medium	Low	Medium
	HE	High emission scenario with adjustment of the electricity mix	Medium	Medium	High	Medium
	LS	Low emission scenario with adjustment of the steam source	Medium	Medium	Medium	Low
	HS	High emission scenario with adjustment of the steam source	Medium	Medium	Medium	High
Most optimistic	LITES	Low emission scenario with adjustment of all parameters	Low	Low	Low	Low
Business-as-usual	HITES	High emission scenario with adjustment of all parameters	High	High	High	High

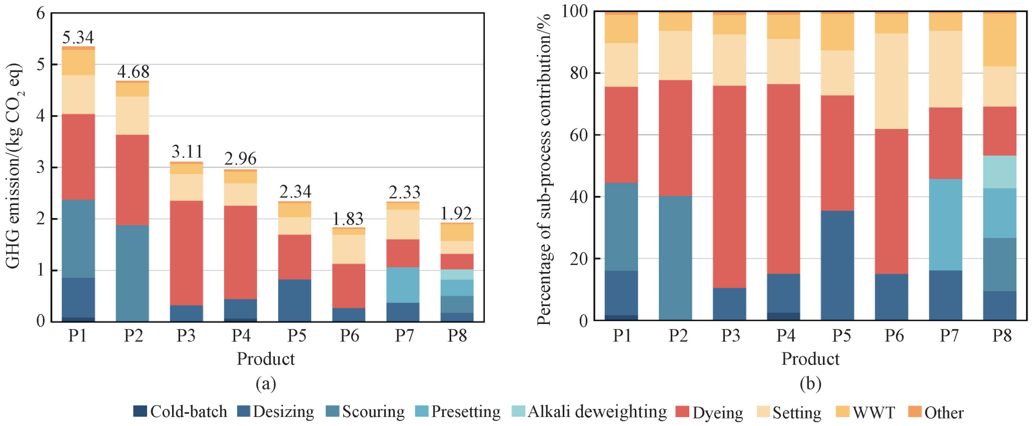
2 Results and Discussion

2.1 GHG emissions from synthetic textile dyeing and finishing process and comparison analysis

Figure 3(a) illustrates the GHG emissions of the eight products from the dyeing and finishing process, highlighting the contributions of each sub-process. Total GHG emissions vary from 1. 83 to 5. 34 kg CO_2 eq across the eight products, with an average value of 3. 06 kg CO_2 eq per kilogram of product from the dyeing and finishing process. A comparison of the airflow dyeing cases (P5, P6, and P7) and overflow dyeing cases (P1, P2, P3, P4, and P8) reveals that airflow dyeing cases exhibit superior environmental performance in general. The average GHG emissions for airflow dyeing cases are

2.17 kg CO_2 eq, which is lower than 3.60 kg CO_2 eq calculated for overflow dyeing cases. This difference arises from the principle of the dyeing methods. In airflow dyeing, an atomized dye solution is sprayed onto the textile by air, drastically reducing the liquor ratio. Lower liquor ratios mean that less energy is required to heat the dye bath, thereby reducing GHG emissions compared to overflow dyeing[41-42]. Additionally, P8 is an exception, potentially due to the higher area density (the mass of the textile per square meter) of P8. The liquor ratio is not only influenced by the dyeing method but is also partially affected by the area density of the textile.

Figure 3(b) provides a detailed breakdown of the contributions of each sub-process to the total GHG emissions in the dyeing and finishing process. Among the pretreatment, dyeing, finishing, and WWT units, the dyeing unit accounts for the highest GHG emissions, with an average of 1.23 kg CO_2 eq (ranging from 0.30 to 2.03 kg CO_2 eq). This can be attributed to the high temperature of approximately 130 ℃ and the extended duration of the dyeing process, which typically lasts twice as long as pretreatment[16]. However, for P7 and P8, the GHG emissions from the dyeing process are notably lower than those of the pretreatment. This may be due to the addition of a presetting step in the pretreatment units for P7 and P8. Synthetic fibers tend to shrink upon exposure to heat unless their internal structure is stabilized at a higher temperature than that encountered in subsequent processing stages. For certain high-quality textiles, presetting before dyeing is employed to control shrinkage[43]. The pretreatment process, which includes cold-batch, desizing, scouring, presetting, and alkali deweighting, is the second largest source of GHG emissions, averaging 1.04 kg CO_2 eq (ranging from 0.28 to 2.40 kg CO_2 eq). Major sources of GHG emissions in this stage include desizing, scouring, and presetting. Previous LCA studies have consistently identified desizing and scouring as primary sources of GHG emissions in pretreatment[44-45]. In the finishing units, the average GHG emissions are 0.54 kg CO_2 eq (ranging from 0.26 to 0.80 kg CO_2 eq). The setting, which imparts dimensional stability, shape retention, and crease resistance to thermoplastic synthetic fibers, is a major source of GHG emissions in this unit. Lastly, WWT generates the lowest emissions, average of 0.25 kg CO_2 eq (ranging from 0.12 to 0.49 kg CO_2 eq). However, for P8, WWT contributes more to GHG emissions (17%) than the setting process (13%). This discrepancy is likely due to the high COD of alkali-deweighting wastewater, which results in higher GHG emissions from the WWT process[46].



(a)

(b)

Fig. 3 GHG emissions of eight products: (a) total emissions; (b) sub-process contributions

Table 5 compares the GHG emissions from the dyeing and finishing process across different studies, highlighting variations in emissions due to differences in materials, technologies, and system boundaries.

Table 5 Comparison of GHG emissions from dyeing and finishing process in different studies

Dyeing method	Material	GHG emission/(kg CO_2 eq/FU)	Contribution to GHG emission/%				Ref.
			Pretreatment	Dyeing	Finishing	Others	
Continuous dyeing	Cotton woven fabric	4.11	27	31	36	6	[47]
Pad dyeing	Cotton fabric	13.52	71	24	4	2	[45]
Softflow dyeing	Organic cotton knitted fabric	12.672	—	96.6	2.2	1.2	[48]
		17.307	—	97.5	1.6	0.9	[48]
Non-silicate cold pad batch dyeing	Organic cotton knitted fabric	7.057	—	93.3	4.6	2.1	[48]
—	Polyester	8.8	—	—	—	—	[49]

As shown in Table 5, the research on GHG emissions from the dyeing and finishing process of synthetic textiles is limited compared to studies on cotton fabrics. This scarcity could be largely attributed to the prevailing preference for cotton among consumers over the past several decades. However, with advancing technology, synthetic textiles are experiencing improvements in both comfort and functionality, potentially altering consumer preferences in the future. The GHG emissions (ranging from 1.83 to 5.34 kg CO_2 eq) in this study are lower than those of earlier studies. This difference might be related to discrepancies in the dyeing and finishing process, inconsistencies in the system boundary, as well as outdated data (given the development in energy efficiency and equipment since the time of prior studies). Since 2010, energy consumption in China's dyeing and finishing sector has significantly declined, by 20%[50] from 2010 to 2015 and by 15%[40] from 2016 to 2020. The primary sources of GHG emissions in the dyeing and finishing process differ greatly. In the case of continuous dyeing, the finishing unit is the primary source of emissions (36%). However, in the case of pad dyeing, the pretreatment unit accounts for 71% of the total GHG emissions. This is because the two cases have different process flows, which influence the energy distribution among the three units of pretreatment, dyeing, and finishing. The research in Du et al.[47] had a complex process that included tentering, preshrinking, and functional finishing stages, which required a lot of energy. In contrast, in the latter case, stages in the pretreatment unit (e.g., scouring, oxygen bleaching, mercerizing, brushing, full-width washing, and baking) account for three-quarters of the total steam consumption. Given the continuous development of dyeing technologies and advancements in energy management, it is essential to assess the GHG emissions under current conditions. This assessment could provide crucial guidance for emission mitigation initiatives, promoting the green development of the dyeing and finishing sector.

2.2 Key contribution analysis

The factors contributing to GHG emissions in the dyeing and finishing process in eight products are illustrated in Fig. 4.

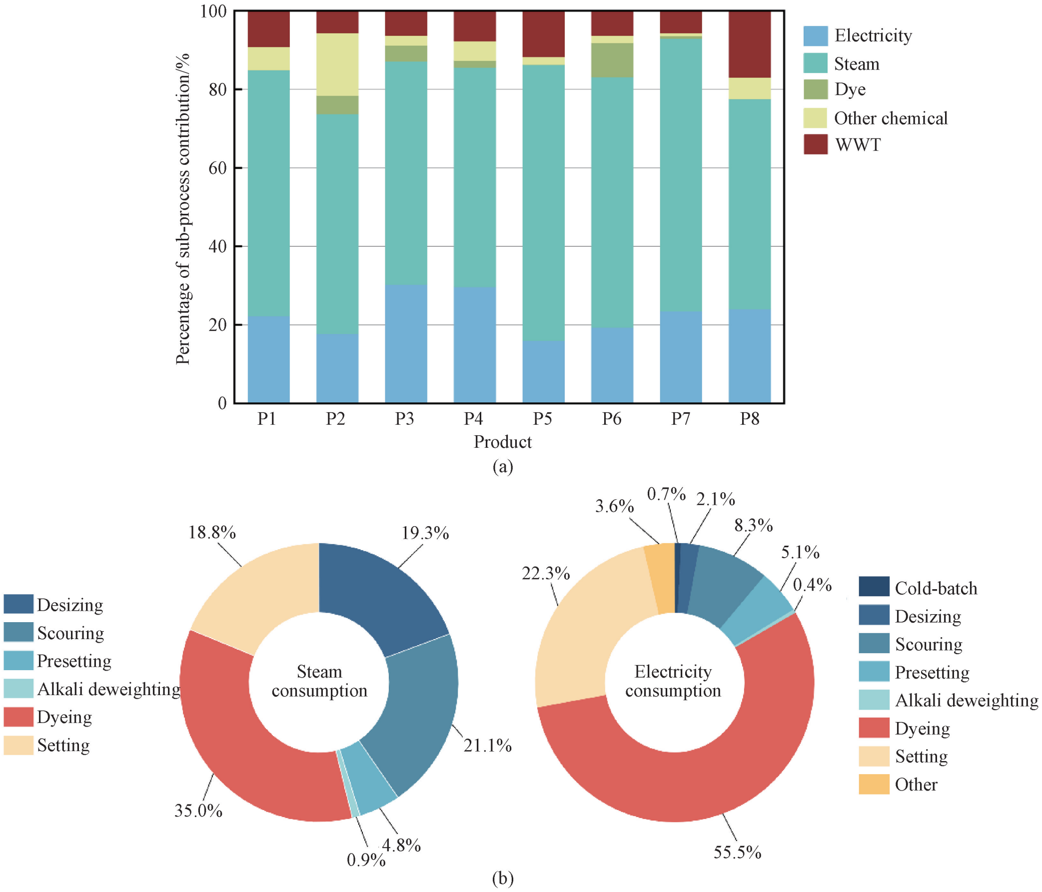


Fig. 4 Key contribution analysis: (a) energy and other substances' contribution to GHG emissions; (b) percentage of energy consumption for each sub-process

Steam consumption emerges as the primary contributor, accounting for 53.43% to 70.23% of the total emissions. The steam used in the production process is supplied by a local thermal power plant, where coal combustion in boilers heats water to produce steam. Due to the high thermal energy requirements of the dyeing and finishing process, significant amount of steam is needed to maintain elevated temperatures. Specifically, desizing and scouring are conducted at a temperature of approximately 100 ℃, presetting at 190–199 ℃, dyeing at 130 ℃, and setting at 160 – 180 ℃. Electricity consumption, which powers pumps, electric motors, machines, and devices[51], also significantly contributes to GHG emissions, ranging from 16.05% to 30.33%. In China, a large portion of the electricity is generated from coal (61.7%), with only 3.0% from natural gas, 0.1% from oil, 4.7% from nuclear power, 15.1% from hydropower, 8.5% from wind power, and 6.9% from solar photovoltaic and other renewable sources[52]. This heavy reliance on coal, driven by its cost advantages and limited domestic supplies of oil and natural gas[53], amplifies GHG emissions throughout energy production. GHG emissions from the consumption of dyes and other chemicals range from 1.38% to 20.57%. Sodium carbonate (Na_2CO_3) and sodium sulfate (Na_2SO_4) are two contributors, particularly in the dyeing process of P2, which involves synthetic fibers and cotton blends. For cotton dyeing, reactive dyes necessitate the use of Na_2SO_4 to reduce the buildup of negative charges on the fiber surface, thereby enhancing dye absorption[54-55]. Direct GHG emissions from WWT account for 5.63% to 16.99% of total emissions. These emissions are linked to the COD concentration and the volume of wastewater. The GHG emissions from sub-process wastewater in WWT process are shown in Table 6. Despite the pretreatment process producing less wastewater than dyeing, the higher COD concentration, particularly from alkali deweighting, contributes to elevated GHG emissions from the WWT in pretreatment.

Table 6 GHG emissions from sub-process wastewater in WWT process

Wastewater source		GHG emission (kg CO_2 eq/FU)							
		P1	P2	P3	P4	P5	P6	P7	P8
Pretreatment	Desizing	0.17	—	0.06	0.09	0.22	0.07	0.10	0.04
	Scouring	0.19	0.16	—	—	—	—	—	0.14
	Alkali deweighting	—	—	—	—	—	—	—	0.11
Dyeing	Overflow	0.13	0.10	0.13	0.13	—	—	—	0.03
	Airflow	—	—	—	—	0.06	0.05	0.03	—
Total		0.49	0.26	0.19	0.22	0.28	0.12	0.13	0.32

2.3 Sensitivity analysis

In this study, sensitivity analysis was conducted to identify which parameters were most important in influencing the variability of GHG emissions. To clearly explain the significance of each parameter, we reduced each parameter by 10% and examined the magnitude of the changes in total GHG emissions resulting from each parameter adjustment.

The bubble diagram (Fig. 5) illustrates the magnitude of the changes in GHG emissions due to the alteration in each parameter, with the area of the bubbles reflecting the extent of effect (larger bubbles indicating a greater effect). The results reveal that energy (steam and electricity) consumption is the most important influential parameter, causing an effect higher than 1.0%. A 10% reduction in steam consumption results in a 6.0% – 8.0% decrease in GHG emissions, while a similar reduction in electricity consumption results in a 1.9% – 3.2% decrease. Hence, controlling energy consumption could efficiently reduce GHG emissions. The effect of dyes and other chemicals is relatively small, with less than 1.0% influence. Of these factors, the use of dyes, NaOH, Na_2CO_3, and Na_2SO_4 is the main source of GHG emissions, while the influence of others is negligible.

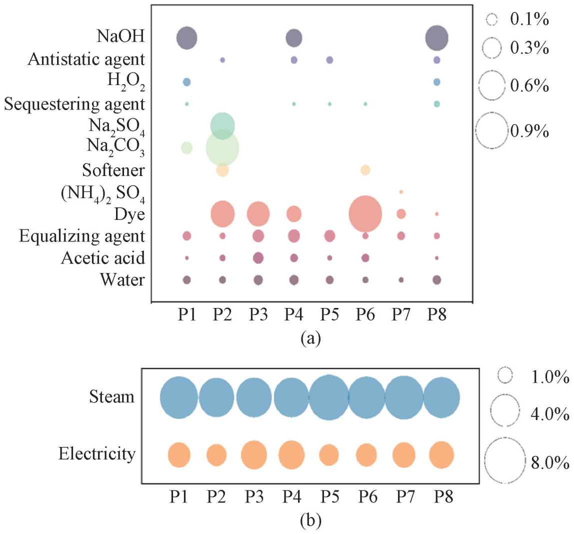
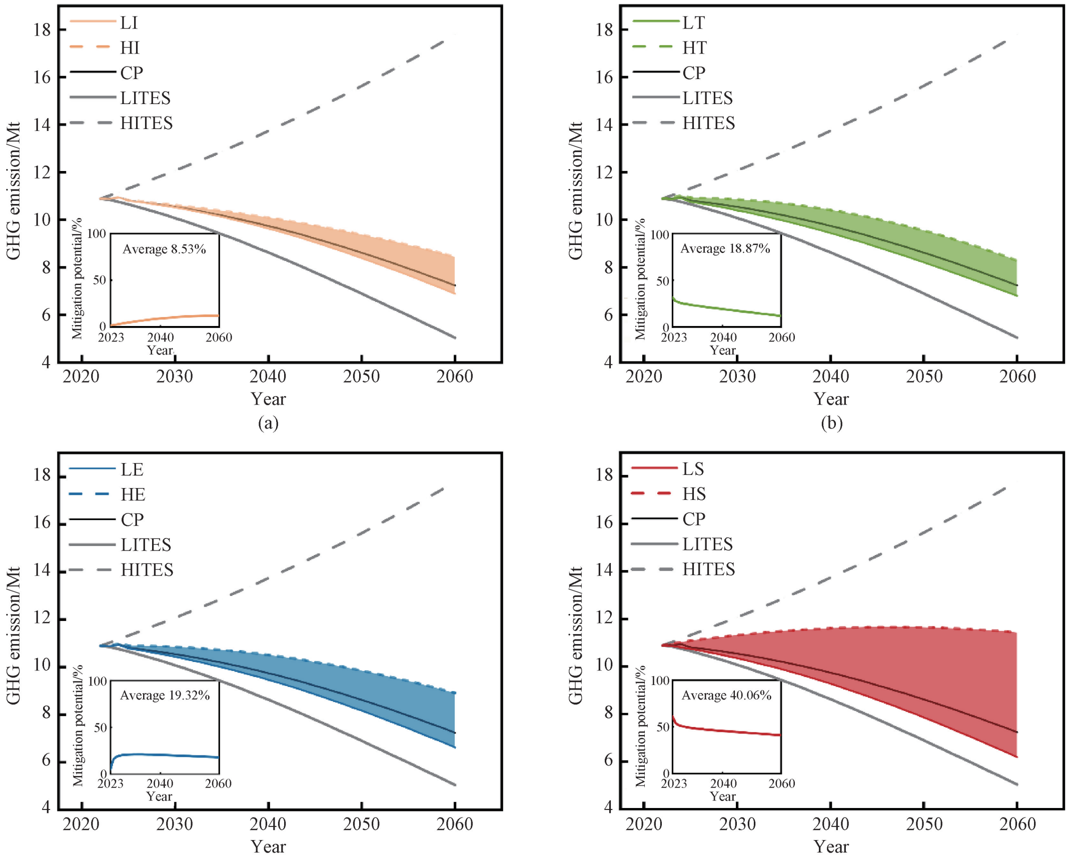


Fig. 5 Sensitivity analysis: (a) materials; (b) energies

2.4 GHG mitigation potential of synthetic textile dyeing and finishing sector

Figure 6 depicts GHG emissions and the mitigation potential under four strategy categories in the colored synthetic textile dyeing and finishing sector by 2060. The main figures illustrate GHG emissions, and the insets focus on the mitigation potential. Specifically, the mitigation potential is quantified as the ratio of two distinct ranges: one defined by the two extreme scenarios of each single parameter (corresponding to its highest and lowest GHG emissions) and the other defined by the LITES and the HITES. Under the HITES, based on the compound annual growth rate of colored synthetic textile production (1.3%), GHG emissions are expected to rise from 10.89 Mt CO_2 eq in 2022 to 17.79 Mt CO_2 eq by 2060. However, under the CP and LITES, emission mitigations of 10.55 Mt and 12.75 Mt CO_2 eq are achieved, respectively. Notably, only the HS fails to meet the goal of achieving a carbon peak by 2030, underscoring the critical importance of adjusting the steam source.



(a)

(b)

(c)

(d)

Fig. 6 GHG emissions and mitigation potential under different scenarios: (a) industry scale; (b) technology penetration; (c) electricity mix; (d) steam source

Among the mitigation strategies, adjusting the steam source offers the highest potential, accounting for 40.06% of the mitigation potential, followed by changes in electricity mix (19.32%), technology penetration (18.87%), and industry scale (8.53%). From 2023 to 2060, optimizing the steam source remains the most effective strategy, consistently contributing over 40% of the mitigation potential. In the dyeing and finishing sector, steam serves as a primary energy source, with current production predominantly reliant on coal-fired boilers due to their significantly lower costs compared to natural gas boilers. This reliance leads to substantial GHG emissions[56]. Future steam production will shift toward cleaner energy sources such as natural gas and biomass, gradually replacing coal to achieve lower GHG emissions. The mitigation potential from changes in electricity structure remains stable at around 19%, but is only 5.05% in 2023. This can be attributed to the actual electricity mix data from that year. The data reveals how China's rapid economic recovery leads to a surge in electricity demand. To meet this heightened demand, relying on thermal power has been crucial for maintaining a stable energy supply[57]. This has limited the contribution of clean energy to emission mitigation efforts, despite China's ongoing push for clean energy development. Before 2035, the mitigation potential of technology penetration exceeds that of the electricity structure, as it primarily reduces energy consumption. However, after 2035, as the power grid becomes cleaner, the significance of further reducing energy consumption declines, allowing electricity structure optimization to take on a greater role in long-term emission mitigation. The GHG mitigation potential associated with the industry scale gradually rises from 1.59% in 2023 to 12.16% by

2060. Controlling the industry scale is a long-term strategy that may not yield substantial short-term emission mitigation but lays the groundwork for a future low-carbon transition by gradually adjusting the scale of industry.

Although the four measures discussed can significantly reduce GHG emissions in the dyeing and finishing sector, they are insufficient to achieve the carbon neutrality target by 2060. The primary focus must be on reducing emissions in steam production. In addition to transitioning boiler fuels to cleaner energy sources, the government should enhance boiler combustion efficiency and promote heat pump technology to recover waste heat from high-temperature wastewater, which accounts for approximately 24.9% of the total heat energy loss[58] for steam production. Heat pumps are regarded as a promising technology that can substantially reduce GHG emissions from steam supply and demonstrate great potential for future energy decarbonization[59-60]. Furthermore, beyond improving the power generation structure and reducing coal's share, the government should implement market-driven mechanisms, such as environmental taxes on high-energy-consuming enterprises and subsidies for renewable energy companies, to incentivize emission mitigation. The penetration of advanced dyeing technologies also plays a critical role in reducing GHG emissions. In addition to promoting waterless dyeing technologies to reduce energy consumption, further mitigation can be achieved by optimizing production processes. This could include integrating digital technologies and intelligent production management systems[61-63], reducing equipment idle time, and improving the success rate of one-time dyeing. Lastly, the government should strictly regulate the production capacity of the dyeing and finishing sector to promote industrial upgrades and ensure sustainable development. Collaborative efforts between upstream industries (e.g., dye and chemical production) and the WWT sector are also essential for decarbonization and the achievement of the overall carbon mitigation targets.

3 Conclusions

This study analyzes GHG emissions from synthetic textile dyeing and finishing, revealing that the process emits 3.06 kg CO_2 eq per kg of textile, with dyeing alone accounting for 1.23 kg CO_2 eq. Steam generation, largely from coal, is the primary source of emissions. Airflow dyeing demonstrates lower emissions than conventional methods due to reduced energy needs.

Under the HITES, sector emissions are projected to increase from 10.89 Mt CO_2 eq in 2022 to 17.79 Mt CO_2 eq by 2060. With mitigation efforts, emissions can be lowered to 7.24 Mt (CP) or 5.04 Mt (LITES). Sensitivity analysis highlights steam source adjustment as the most effective mitigation strategy, with a potential mitigation of over 40.06%, followed by improvements in electricity structure (19.32%), technological penetration (18.87%), and industry scale optimization (8.53%). Nevertheless, these measures alone are insufficient to achieve carbon neutrality by 2060. To achieve deeper emission mitigation, it is essential to prioritize the following strategies: 1) scaling clean energy for steam production (e.g., natural gas, biomass, green hydrogen); 2) enhancing boiler efficiency through retrofits and advanced technologies; 3) accelerating the adoption of green energy-saving technologies, including renewable energy integration and energy recovery systems; 4) introducing policy and financial support for low-carbon transitions. Furthermore, a holistic, coordinated approach is necessary to address GHG emissions throughout the entire value chain. This includes collaboration with upstream industries such as the dye and chemical production, and the WWT process to minimize carbon footprints from all stages of production. In conclusion, reaching carbon neutrality in this sector will demand integrated technological and policy actions, supporting China's 2060 goal and enabling sustainable industrial development.

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合成纤维织物染整行业的温室气体排放及减排策略

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摘　要：中国作为全球最大的合成纤维织物生产和消费国，其合成纤维织物染整行业面临可持续发展挑战。合成纤维织物染整行业的温室气体排放情况及潜在减排路径需进一步明晰。该研究通过分析 8 个代表性生命周期评价案例，评估了合成纤维织物染整加工环节的温室气体排放情况。为探讨减排潜力，提出了 4 项减排策略，并基于此制定了 11 种情景。研究结果表明，合成纤维织物在染整加工环节每千克织物的平均温室气体排放为 3.06 kg CO_2 eq（1.83~5.34 kg CO_2 eq），其中染色单元的能源消耗（蒸汽和电力）是主要排放来源。情景分析显示：在一切照旧的情景下，2060 年染整行业温室气体排放可能达到 1 779 万 t CO_2 eq；不同情景下的减排潜力在 35.72% 到 71.65% 之间；在最乐观的情景下，2060 年温室气体排放可能降至 504 万 t CO_2 eq。这些发现为探索合成纤维织物染整行业的关键减排路径提供了重要依据。

关键词：染整；生命周期评价；合成纤维织物；温室气体排放