Comparative Evaluation of Stocking Products Based on Product Life Cycle Assessment

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Abstract: Objective In order to analyze the difference of environmental benefit between different processes of silk stockings products, the article puts forward the method of product life cycle analysis to provide reference for the subsequent selection and optimization of production process of silk stockings products. Methods The representative target products in silk stockings were selected, and the full life cycle model of production, use and waste of target products was established by product life cycle method. The two technologies were compared and evaluated quantitatively by analyzing relevant environmental impact indexes, and the reasons for the difference were analyzed by refining the product production process. Conclusion Dope dyed stocking fabric is more environmentally friendly than traditional dyed stocking fabric. The production process of a product is the link that has the greatest impact on the environment in the entire life cycle and the main link that causes the environmental differences between the two processes. The product life cycle model established in this paper can be used as a reference for the life cycle analysis of other similar fabric products, and it proposes a normalized index suitable for evaluating environmental benefits in other industries.

1. Introduction

Silk stockings are widely used in clothing fabrics and other industries because of their good flexibility, economical benefits, easy washing and drying. However, while the stockings products bring convenience to people, the waste gas and wastewater discharged from the production process also bring serious environmental pollution problems, which have become an important factor hindering the sustainable development of the stockings industry. This article analyzes the impact of different production processes of stockings on the environment through the product life cycle assessment method (LCA) and seeks the application prospects of the life cycle method in other industries, and seeks the way of green manufacturing in the stockings industry.

2. Materials and square method

2.1. The status quo of China's stockings industry and the prospect of green manufacturing

Since 21 century, with the living standards continuously improve, people's demand for clothing category is also growing. In 2019, the size of chinese stockings retail market reached 26.64 billion yuan, and it is growing at a rate of about 10%. At the same time, the chemical fiber industry represented by silk stockings is one of the major polluting industries in China, and the total amount of wastewater discharged by the textile industry ranks fifth in the total discharge of various industrial sectors in the country. The "Thirteenth Five-Year Development Outline for the Textile Industry" stipulates the green
development goals of the textile industry: by 2020, the energy consumption per unit of textile industry's added value will be reduced by 18%, and the total discharge of major pollutants will be reduced by 10%\cite{3}.

Designers focus on green manufacturing requirements of product lifecycle, aimed at producing products from design, raw production, transport to report the whole process of treatment of waste on the environment of negative effects to a minimum\cite{4}. Therefore, reducing the environmental impact of stockings products throughout the life cycle has become an urgent problem in the stockings industry.

![Green manufacturing full life cycle](image)

**Fig 1 Green manufacturing full life cycle**

### 2.2. Application of Product Life Cycle Method in the Stocking Industry

Product life cycle assessment methods are currently widely used to quantify the environmental impact of products throughout the life cycle. In the "cradle to grave" product life cycle, it includes the acquisition of raw materials, manufacturing, packaging and transportation, use process, and disposal and recycling\cite{5,6}. LCA can either assist enterprises in industry improved technology and design, but also support environmental protection departments to develop government policies related to the environment, but also guide consumers to choose eco-friendly products. In China's LCA research, Liu Muyu, Gao Hongwei and others used the LCA method to model different bridge examples and compare their environmental performance differences\cite{7}; Han Zhenyu comprehensively determines the best material from a subjective and objective perspective by combining the LCA method, analytic hierarchy process, entropy method and ideal point method\cite{8}; Shi Xiaoqing, Sun Zhaoxin, Li Xiaonuo and others used LCA method to compare and analyze the environmental emission of Beijing electric taxi and fuel taxi\cite{9}.

In the production process of stockings, silk stockings are generally dyed in two ways: traditional dyeing and dope dyeing. Is generally believed that, compared to traditional dyeing method, dope dyeing method is economical and environmentally friendly, in line with green manufacturing requirements. Foreign studies have shown that the modal fabric with dope dyeing method reduces the environmental impact by 40% to 60% compared with the traditional dyeing method. However, this data is based on European fabric data, or may deviate from the actual situation in China\cite{10}. The LCA work in China is in the development stage, and the data of various industries are not complete. There are still blanks in the research on traditional dyeing and dope dyeing of silk stockings. There has been only qualitative evaluation and lack of quantitative evaluation. It is impossible to determine the environmental friendliness of the two processes. The use of domestic data to quantitatively compare the environmental impact of the two processes can not only provide support for China's textile industry to vigorously promote the dope dyeing method, but also provide inspiration for future improvements and optimization of the silk stocking industry process flow.

Product life cycle assessment is divided into 4 steps, as 2.3 ~ 3.2.

#### 2.3. Target definition and scope definition

In this study, silk stocking fabric was used as the target product, and the environmental impact caused by the whole life cycle of stockings using two production processes was analyzed with the help of the IKE eFootprint platform. Plan 1: Using traditional dyeing process; Plan 2: Using dope dyeing process. Other processes are the same.

To fully consider the research objectives to be sufficiently representative, this study specifically uses
PA6 stockings as the research object. PA6, also called nylon 6, is a commonly used raw material for stockings, sportswear and high-end clothing, and has a wide range of applications. Since the dope dyeing process is generally used for colors with a larger output, and black pollution and energy consumption are large, the research on the environmental impact of black stockings is representative.

Tab 1 Target and scope definition

| Software | IKE eFootprint platform |
|----------|-------------------------|
| Target   | Black PA6 stockings     |
| Functional unit | 1t                     |
| Area of research | Production, using, disposal |
| Data age    | 2016                    |
| Fiber fineness | 20D                    |
| Fiber size  | 67tex                   |
| Chemical fiber content | 95% nylon, 5% spandex |

The scope of this research is "from cradle to grave", covering the entire life cycle of the product's energy resource input and emission consumption, including the traceability of the upstream production process of the raw materials for the production of stockings until the resource extraction, and the disposal and recycling of waste stockings.

2.4. List analysis

Data inventory analysis is the beginning of quantitative product life cycle, a complete list needs to include all relevant inputs and outputs of the system elements[11]. By determining the system boundary of the target product, the life cycle model of black PA6 stockings for two production processes is obtained.

The production process is shown in Figure 2, including the production and packaging process of stockings. The traditional dyeing method uses the process of spinning first and then dyeing, while the dope dyeing method uses the process of dyeing first and then spinning.

The using process includes the transportation and washing of stockings. The transportation distance is estimated at 92km per ton of stockings, and light gasoline trucks are selected as transportation means. The washing process is estimated according to 22.5t of water and 4.5kg of detergent per ton of stocking products. Due to the short life of stockings, assuming stockings life of 3 times. Stockings discarding process comprises producing products landfill and incineration processes. Silk stockings are dry waste and are not easy to recycle. There are only two disposal methods: landfill and incineration. Take Guangzhou, a city with a large demand for stockings as an example. According to the garbage disposal method of Guangzhou in 2016, the ratio of landfill to incineration is 21:4 make an estimate[12].

The data used in the research comes from: industry statistics, "Textile Industry Energy Conservation, Emission Reduction and Cleaner Production Audit", cleaner production evaluation index system, industry standards, corporate statistics, corporate environmental impact assessment reports, Gabi
database, China Life Cycle Basic Database (CLCD). All data are traced forward to the upstream material in the actual production process until the production data of the upstream material can be found in the database. This research model does not include materials that comply with the cut-off principle.

3. Results and analysis

3.1. Environmental impact assessment

Modeling and calculating the two programs, transform the input and output data of the entire life cycle of PA6 black stockings into environmental indicators, and compare the environmental impact differences of the two processes. Among various environmental impact indicators, the environmental impact indicators with larger values are selected as climate change (GWP), water consumption (WU), and primary energy consumption (PED). The comparison of environmental indicators of the two methods is shown in Table 2, Table 3 and Table 4.

| Tab 2 Comparison of climate change (GWP) index (unit: kg CO2 eq) |
|---------------------------------------------------------------|
| production process | Use process | Abandonment process | Total period |
| Traditional dyeing method | 19798.84 | 13.20 | 120.14 | 19932.20 |
| Dope dyeing method | 13590.89 | 13.20 | 118.89 | 13722.98 |

| Tab 3 Comparison of resource depletion-water (WU) index (unit: kg) |
|---------------------------------------------------------------|
| production process | Use process | Abandonment process | Total period |
| Traditional dyeing method | 626169.17 | 22940.44 | -117.15 | 648992.45 |
| Dope dyeing method | 180308.70 | 22940.44 | -126.51 | 203122.63 |

| Tab 4 Comparison of primary energy demand (PED) index (unit: MJ) |
|---------------------------------------------------------------|
| production process | Use process | Abandonment process | Total period |
| Traditional dyeing method | 240395.86 | 173.49 | -343.94 | 240225.40 |
| Dope dyeing method | 155973.36 | 173.49 | -415.09 | 155731.76 |

It can be seen from the above tables that the stocking products produced by the dope dyeing method have significantly less climate change (GWP), water consumption (WU), and primary energy consumption (PED) in the whole life cycle than the traditional dyeing method. Only 68.85%, 31.30%, 64.83% of the traditional dyeing method. The data better supports the conclusion that the silk stockings produced by the dope dyeing process is more environmentally friendly than the silk stockings produced by the traditional dyeing process.

As far as the product life cycle stage is concerned, the production process is the link that has the greatest impact on the environment during the entire life cycle of the stockings. Whether it is traditional dyeing or dope dyeing, the environmental impact accounts for more than 88%; the environmental impact during use affect a smaller proportion of the total life cycle, mainly due to transport and washing.
instructions are not part of the environmental impacts, if the study is a longer service life of other clothing, the influence of the use link on the whole life cycle may be increased; The indicators of water consumption (WU) and primary energy consumption (PED) in the abandonment process are negative, because in the abandonment process, part of the waste is burned to generate electricity, which offsets part of the negative environmental impact and has a positive effect on the environment.

3.2. Results interpretation
This study continues to explore the reasons for the differences in the values of different environmental impact indicators caused by the two processes. Since the contribution of stockings to climate change (GWP), water consumption (WU), and primary energy consumption (PED) during the life cycle of stockings mainly comes from the production process, the following will analyze the contribution of each link of the production process of the two methods to environmental indicators.

According to Figure 2, the production process is subdivided into five processes: DTY wire production, spandex yarn production, socks, staining, and packaging. The difference between traditional dyeing and dope dyeing lies in the production and dyeing process of DTY wire: in traditional dyeing process, dyeing is an independent process; in dope dyeing process, dyeing belongs to the production process of DTY wire.

The impacts of the two schemes on climate change (GWP), water consumption (WU), and primary energy consumption (PED) during the production process are shown in Figure 3, Figure 4, and Figure 5, respectively. It can be seen from the figure that the traditional dyeing method and the dope dyeing method have similar impacts on the three environmental indicators caused by the spandex yarn production, socks and packaging processes, but the independent dyeing process in the traditional dyeing process has a greater impact on the three environmental indicators, accounting for 32.84%, 72.07%, and 35.55% of the production process, reflecting that the large amount of water, electricity and printing and dyeing materials and auxiliaries consumed by the traditional dyeing method in the dyeing process are the main factors that cause the serious environmental impact of the traditional dyeing method. In contrast, because the dope dyeing method uses the pre-spinning coloring technology, the fiber is colored in the initial form, which greatly reduces the environmental impact of the production of stockings.

Modeling and analyzing the full life cycle of black nylon 6 stockings produced by traditional dyeing method and dope dyeing method by LCA method, the data show that climate change (GWP), water consumption (WU), primary energy consumption (PED) for the three environmental indicators, the dope dyeing method is significantly more environmentally friendly than the traditional dyeing method. By analyzing the production process to explore this difference, we can know that the dyeing process in the
production process of the traditional dyeing method is the main reason for the poor environmental benefits of the traditional dyeing method.

4. Discussion

(1) The study of 95% nylon, 5% spandex content of PA6 stockings yield product. As FIG.4 and FIG.5 can be seen, in the production process of the commonly used dope coloring PA6 stockings, although the spandex content is only 5%, its impact on the three environmental indicators of water consumption (WU) and primary energy consumption (PED) accounted for 18.67% and 9.42% of the production process. If the research object is changed to other fabrics with different spandex content, the corresponding environmental impact indicators can be adjusted according to the ratio of spandex and DTY filaments to approximate the environmental impact of different fabrics.

Take 25% of the dope dyeing fabric as an example, when the spandex content increases from 5% to 25%, the DTY wire content drops from 95% to 75%. Using $G_1'$ to express the climate change index during the production process of 25% spandex fabric, and using $G_2'$ to express the climate change index during the production process of 25% spandex fabric DTY wire. Seeing formulas (1) and (2) for approximate calculation of $G_1'$ and $G_2'$; for the same reason, seeing formulas (3) and (4) for approximate calculation of $G_1''$ and $G_2''$.

$$G_1' = G_1 \times (25\% + 5\%)$$ (1)

$$G_2' = G_2 \times (75\% + 95\%)$$ (2)

$$G_1'' = G_1 \times (45\% + 5\%)$$ (3)

$$G_2'' = G_2 \times (55\% + 95\%)$$ (4)

Through calculation, we can get the data of climate change (GWP), water consumption (WU), and primary energy consumption (PED) in the production process of DTY wire and spandex for 25% spandex content dope dyeing fabric and 45% spandex content dope dyeing fabric. The data is shown in Table 5.

| Tab 5 Environmental effects of different polyurethane content on the production of DTY filament and polyurethane |
|---------------------------------------------------------------|
| 5% spandex | 25% spandex | 45% spandex |
| DTY wire ($G_2$) | Spandex ($G_1$) | Total ($G_3$) | DTY wire ($G_2'$) | Spandex ($G_1'$) | Total ($G_3'$) | DTY wire ($G_2''$) | Spandex ($G_1''$) | Total ($G_3''$) |
| GWP(kg CO₂ eq) | 11489.33 | 896.98 | 12386.31 | 9070.52 | 4484.9 | 13555.42 | 6651.72 | 8072.82 | 14724.54 |
| WU(kg) | 84548.41 | 33662.17 | 118210.58 | 66748.74 | 168310.85 | 235059.59 | 48949.08 | 302959.53 | 351908.61 |
| PED(MJ) | 125096.66 | 14698.83 | 139795.49 | 98760.52 | 73494.15 | 172254.67 | 72424.38 | 132289.47 | 204713.85 |

The dope dyeing process includes four processes: DTY wire production, spandex production, socks and packaging. Regardless of the difference in the environmental impact caused by changing the spandex content on the socks and packaging process, the environmental impact caused by the production of DTY wire and spandex is used to approximate the difference in environmental impact caused by the production process of dyeing fabrics with different spandex content. It can be seen from Table 5 that with the increase of spandex content, the three environmental indicators data of climate change (GWP), water consumption (WU), and primary energy consumption (PED) all increase, and water consumption (WU), primary energy consumption (PED) refers to the standard increase significantly, spandex production process gradually replaced DTY silk production process, affecting the whole production process to become part of the largest on the environment. Based on the above analysis, it can be concluded that in the dope dyeing process, optimizing the spandex production process will effectively reduce the environmental impact of the entire production process.

(2) The life cycle assessment method adopted in this study can not only provide reference for environmental professionals, but also provide inspiration for other industries. As a product green evaluation technology, the product life cycle assessment method (LCA) can provide a reference for
green manufacturing, but the current LCA method has a high threshold, which is mainly reflected in the fact that there are many evaluation types calculated through LCA software modeling and calculation, which is lacking in specific industries. Pertinence, it is difficult for non-professional users to consider multiple indicators at the same time. In view of the above-mentioned difficulties, it is possible to consider establishing weighting factors based on different needs under actual conditions to form normalized indicators to facilitate the specific analysis of environmental indicators in different industries.

Taking the production process of PA6 stockings in this study as an example, list the environmental impacts of the production process of dope dyeing PA6 stockings, and the results are shown in Table 6.

Tab 6 Environmental impact data of the production process of PA6 silk stockings dyed by stock solution

| Impact type | PED/10^3 | ADP/10^4 | WU/10^3 | GWP/10^2 | ODP/10^5 | AP/10^6 | RI/10^1 | POFP/10^1 | EP/10^1 | ET/10^0 |
|-------------|----------|----------|----------|----------|----------|---------|---------|-----------|---------|---------|
| DTY wire    | 125.0967 | 275.2744 | 84.5484  | 114.8933 | 49.1703  | 22.0192 | 58.8485 | 61.9917   | 18.0159 | 135.3325 |
| Spandex yarn| 14.6988  | 265.7278 | 33.6622  | 8.9698   | 1.9085   | 5.3281  | 23.0921 | 6.6341    | 2.7007  | 7.7787  |
| Socks       | 10.0080  | 4.9846   | 54.6020  | 7.1167   | 0.3227   | 3.7536  | 11.0509 | 45.4953   | 2.9046  | 7.7787  |
| Package     | 6.1699   | 9.6921   | 7.4961   | 4.9290   | 0.1559   | 0.7318  | 2.3192  | 1.2971    | 0.7318  | 2.3192  |
| Total       | 155.9734 | 555.6789 | 180.3087 | 135.9089 | 51.5573  | 33.1740 | 97.0497 | 74.8360   | 23.9728 | 147.2525 |

Define the total environmental impact caused by the production of PA6 stockings by dope dyeing method as \( I_t \), then:

\[
I_t = PED + ADP + WU + GWP + ODP + AP + RI + POFP + EP + ET \quad (5)
\]

Through the calculation, \( I_t = 350073.0158 \), and use this as a benchmark to establish the index \( K \) corresponding to \( I_t \), and define the total environmental impact caused by the production process of the dope dyeing PA6 stockings as \( K_t = 100 \). According to this method, data on the whole life environmental impact of fabrics with different spandex content can be obtained, as shown in Table 7.

Tab 7 Influence data of the whole life environment cycle of fabric with different spandex content

| Environmental impact K | 5%spandex fabric | 25%spandex fabric | 45%spandex fabric |
|------------------------|------------------|------------------|------------------|
|                        | Dope dyeing method | Traditional dyeing method | Dope dyeing method | Traditional dyeing method | Dope dyeing method | Traditional dyeing method |
| K_{DTY wire}           | 63.22            | 63.02            | 49.91            | 49.75            | 36.60            | 36.49            |
| K_{spandex yarn}      | 14.08            | 12.10            | 70.38            | 60.52            | 126.68           | 108.93           |
| K_{socks}             | 18.66            | 18.66            | 18.66            | 18.66            | 18.66            | 18.66            |
| K_{staining}          | 0                | 155.49           | 0                | 155.49           | 0                | 155.49           |
| K_{packaging}         | 4.05             | 4.01             | 4.01             | 4.01             | 4.05             | 4.01             |
| K_{total}             | 100.00           | 253.28           | 142.99           | 288.42           | 185.99           | 323.57           |

It can be seen directly from Table 7 that, without considering the impact of changing the spandex content on the dyeing process, the environmental impact data of 5%, 25% and 45% spandex content fabrics under the dope dyeing process and traditional dyeing process under the full life cycle environmental impact data. This method can be applied to similar products as well as different types of products, so that people in different industries can quickly compare and judge the environmental benefits of products.

5. Conclusion

In this paper, 5% spandex content PA6 black stockings is regarded as the target product, using the LCA method to analyze and compare the environmental impact differences in the whole life cycle of stockings formed by the traditional dyeing process and the dope dyeing process, and explore the reasons for the differences from the production process. This can provide a reference for process selection and optimization. In addition, the article proposes to establish normalized indicators, which can provide reference for non-LCA practitioners. It should be noted that the environmental indicators concerned by
different industries may be different. Therefore, it is also necessary to reasonably allocate the weight of each environmental indicator in the normalized indicator according to the actual situation and the importance of the environmental indicator.

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