

Development and application of a green degree evaluation framework for the environmental sustainability of clothing

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ABSTRACT – REZUMAT

Development and application of a green degree evaluation framework for the environmental sustainability of clothing

The production, use, and disposal of clothing contribute significantly to environmental pollution and resource depletion, necessitating robust methodologies to evaluate environmental sustainability. Nevertheless, a holistic framework for evaluating the environmental sustainability of clothing is still absent. To bridge this gap, this study introduces the concept of green degree to develop a holistic evaluation framework for clothing, which comprises an evaluation system and an evaluation model. The clothing green degree evaluation system is based on the principles of environmental friendliness, technological advancement, and economic rationality, and is composed of green material, green design, green production, green quality, and green packaging. TFN-AHP and grey clustering method were integrated to develop the evaluation model. Among the five evaluation dimensions, green production and green material received the highest weights, at 36.89% and 33.64% respectively. To validate the proposed model, a men's polo shirt was evaluated as a case study. With a score of 3.647, the shirt was evaluated as 'green' grade on the five-tier green degree scale, a result consistent with its actual environmental properties. Through this green degree evaluation framework, the environmental sustainability of clothing can be evaluated, thereby providing a scientific basis for product development and classification strategies.

Keywords: environmental sustainability of clothing, clothing green degree, evaluation framework, TFN-AHP, grey clustering method

Dezvoltarea și aplicarea unui cadru de evaluare a gradului de ecologie pentru sustenabilitatea de mediu a articolelor de îmbrăcăminte

Producerea, utilizarea și eliminarea articolelor de îmbrăcăminte contribuie semnificativ la poluarea mediului și la epuizarea resurselor, ceea ce impune dezvoltarea unor metodologii solide pentru evaluarea sustenabilității de mediu. Cu toate acestea, un cadru holistic pentru evaluarea sustenabilității de mediu a articolelor de îmbrăcăminte lipsește încă. Pentru a acoperi acest gol, studiul de față introduce conceptul de grad de ecologie, în vederea dezvoltării unui cadru de evaluare holistic pentru articolele de îmbrăcăminte, care cuprinde un sistem de evaluare și un model de evaluare. Sistemul de evaluare a gradului de ecologie al îmbrăcămintei se bazează pe principiile de protejare a mediului, progresului tehnologic și raționalității economice, și este compus din cinci parametri: materiale ecologice, design ecologic, producție ecologică, calitate ecologică și ambalaj ecologic. Metodele TFN-AHP și de grupare gri (grey clustering) au fost integrate pentru a dezvolta modelul de evaluare. Dintre cei cinci parametri de evaluare, producția ecologică și materialele ecologice au primit cele mai mari ponderi, de 36,89%, respectiv 33,64%. Pentru validarea modelului propus, un tricou polo pentru bărbați a fost evaluat ca studiu de caz. Cu un scor de 3,647, tricoul a fost clasificat ca „ecologic” pe o scară cu cinci trepte a gradului de ecologie, rezultat care corespunde proprietăților sale reale de mediu. Prin intermediul acestui cadru de evaluare a gradului de ecologie, sustenabilitatea de mediu a articolelor de îmbrăcăminte poate fi evaluată riguros, oferind astfel o bază științifică pentru dezvoltarea produselor și strategiile de clasificare.

Cuvinte-cheie: sustenabilitatea de mediu a articolelor de îmbrăcăminte, gradul de ecologie al îmbrăcămintei, cadru de evaluare, metoda TFN-AHP, metoda de grupare gri

INTRODUCTION

A major contributor to global pollution, the textile and clothing industry generates significant greenhouse gas emissions and water pollution [1]. Escalating environmental challenges necessitate that the industry embrace responsibility for mitigating its impact. This entails a critical balance between economic growth, industrial innovation, and ecological conservation to ensure a sustainable future [2]. Nevertheless,

despite this recognized urgency, the industry persists as a model of high input, consumption, and pollution, coupled with low yield – an operational pattern far removed from the goals of sustainable management [3].

Sustainable development requires responsible consumption and production by enterprises and consumers, and ensuring the environmental sustainability of products is an effective way to achieve this goal [4].

Nevertheless, most clothing products are not sustainable, either in the nature of the product or in the quantity of the product. First of all, it is a recognised fact that clothing products have a serious impact on the environment [5]. The environmental impact of clothing products during their life cycle is manifested by: i) High water consumption, water eutrophication and soil pollution due to extraction of raw materials from natural resources [6]; ii) Emissions of BTEX compounds, NO_x, SO₂ and other harmful compounds during the extraction of raw materials from petrochemical resources [7]; iii) Greenhouse gas emissions and water pollution from industrial production [8]; iv) High water consumption and water eutrophication due to consumer washing [9].

Secondly, there is an overproduction of clothing, which results in a huge amount of waste. In the clothing industry, fast-changing customer needs, seasonal product fluctuations, low high-tech content of products and a wide range of suppliers require enterprises to achieve fast, low-cost production of products [10]. Nevertheless, fast-changing fashion trends and fierce market competition have led to a growing oversupply of clothing, which results in a huge waste of resources. In addition, to maximise profits, the majority of clothing enterprises do not invest too much in selecting sustainable raw materials, introducing advanced equipment, improving working conditions and reducing production pollution [11]. In conclusion, for promoting the sustainable development of the textile and clothing industry, it is essential to improve the environmental sustainability of clothing. Nevertheless, a scientific and comprehensive evaluation system and methodology are required to improve the environmental sustainability of clothing. At present, eco-label and carbon-labelling are the most common sustainability evaluation criteria for clothing, including OEKO-TEX, Global Organic Textile Standard [12], Carbon Reduction Label, Carbon Free TM Product Certification label, etc. [13]. Eco-label focuses on the safety of the clothing's material composition and the low toxicity of chemical additives, which regulates the pH level, formaldehyde content, extractable heavy metal content, organotin content, colour fastness of clothing, etc. [14]. Carbon-labelling focuses on the carbon footprint of the clothing at the production stage, which is presented in the form of a grade, a value, etc. [15]. Clothing eco-labels and carbon-labelling guide companies on regulated and green production, as well as facilitating consumers' choice of sustainable products. Nevertheless, with the enrichment of sustainable development concepts and the innovation of green products, sustainability evaluation criteria for clothing need to be enriched as well, which requires an evaluation system for a comprehensive evaluation of the environmental sustainability of clothing [16, 17]. To establish a comprehensive evaluation system, the first step is to select an evaluation method that can fully reflect the environmental sus-

tainability of clothing. At present, the green degree evaluation is a commonly used method for product evaluation, which is derived from the Green Product [18]. Environmental friendliness, technological advancement, and economic rationality are the core dimensions of the green degree evaluation, which can fully quantify the environmental sustainability of a product [19]. In the field of building materials, machine parts, transportation, etc., the green degree evaluation has become a common evaluation method for evaluating the environmental sustainability of their products, and its comprehensive evaluation dimensions can theoretically provide new ideas for evaluating the environmental sustainability of clothing. Nevertheless, green degree evaluation has yet to be applied to the environmental sustainability evaluation of clothing, nor has it been leveraged to create an evaluation system grounded in the distinctive characteristics of clothing product. Therefore, we developed a green degree evaluation framework for the environmental sustainability of clothing, drawing on the concept of green degree and the distinctive characteristics of clothing. Our study contributes to the body of knowledge by providing a holistic evaluation framework for the environmental sustainability of clothing; it also offers a foundation for informing the development of sustainable products.

RELATED THEORY AND WORK

Review of related theories

To establish the clothing green degree evaluation system and model, research experience in the fields of engineering technology and art design is required. Firstly, the clothing green degree evaluation system is a sustainable evaluation system based on clothing product characteristics, which requires discussing the related works on the life cycle of clothing and the characteristics of sustainable clothing. Secondly, this evaluation system is based on the green degree theory, which requires discussing the related works on the product green degree evaluation.

Different types of clothing are produced and processed in different ways, which leads to different life cycles [20]. However, in general, the life cycle of a garment typically includes the stages of raw material extraction, clothing production, retailing, use and end of life [21]. At present, related works have provided a detailed explanation of the concept, the definition, and the stages of the life cycle of clothing, and although different researchers differ in how they define life cycle stages, there is no clear divergence in the basic opinions and findings of the researchers [22, 23]. By synthesizing related works, the life cycle stages of clothing can generally be divided into the raw material extraction and production stage (extraction and production of raw materials for clothing fibres and accessories.), the fabric weaving and clothing manufacturing stage (fabric production and clothing production.), the retailing stage (traditional retail and online retail.), the use and maintenance

stage (washing, ironing, and drying of clothing), and the end-of-life stage (direct reuse, recycling, landfill, or incineration) [8, 21]. The clothing green degree evaluation is one of the methods of product sustainability evaluation, which requires discussing the related works on the characteristics of sustainable clothing. Generally, sustainable clothing is high-quality clothing that minimises pollution and waste of resources, and contributes to human health, based on the principle of environmental protection [24, 25]. Although there is no authoritative definition of sustainable clothing, research generally agrees that sustainable clothing should be sustainable in terms of materials, patterns, and production conditions [26]. Thereby, the characteristics of sustainable clothing generally include the use of environmentally friendly materials [27], the application of sustainable design strategy [28], and efficient and clean production conditions [29]. In addition, the use of environmentally friendly packaging has been recognised in recent years as an essential manifestation of the characteristics of sustainable clothing [30].

At present, there are many research fields that have applied the green degree evaluation to the sustainable evaluation of products [31, 32]; however, there is still a lack of related work on the clothing green degree evaluation. Related works on product green degree evaluation are based on their own research content to establish the evaluation system, which has no uniform requirement for the establishment of the system [33], and the selection of research methods also differs [34]. However, there is one thing in common, as all related works have established their evaluation systems around the environmental, economic, and technical attributes of products, which is consistent with the core dimensions of the green degree evaluation. Thereby, the establishment of the clothing green degree evaluation system should be based on the core dimensions of green degree evaluation, combined with the related works on the life cycle of clothing and the characteristics of sustainable clothing, to establish the evaluation system and select the appropriate evaluation method. In summary, by reviewing the related works on the life cycle of clothing, the characteristics of sustainable clothing, and the product green degree evaluation, we obtained the concept of the clothing green degree: the degree to which a garment is environmentally friendly, technologically advanced, and economically rational throughout its life cycle. The clothing green degree can fully reflect the sustainability of clothing, and the clothing green degree evaluation system is the specific evaluation dimension and content. Thereby, we introduced the green degree evaluation, based on the principles of environmental friendliness, technological advancement, and economic rationality. We established the clothing green evaluation system with five evaluation dimensions: green material, green design, green production, green quality, and green packaging, as shown in figure 1.



Fig. 1. Establishment principle of the clothing green degree evaluation system

The clothing green degree can be expressed by the equation, as shown in equation 1:

$$G_{clo} = f(M_{clo}, D_{clo}, P_{clo}, Q_{clo}, B_{clo}) \quad (1)$$

where G_{clo} is the clothing green degree. M_{clo} is the degree to which a garment is environmentally friendly, technologically advanced, and economically rational in terms of the green materials dimension. D_{clo} is the degree to which a garment is environmentally friendly, technologically advanced, and economically rational in terms of the green design dimension. P_{clo} is the degree to which a garment is environmentally friendly, technologically advanced, and economically rational in terms of the green production dimension. Q_{clo} is the degree to which a garment is environmentally friendly, technologically advanced, and economically rational in terms of the green quality dimension. B_{clo} is the degree to which a garment is environmentally friendly, technologically advanced, and economically rational in terms of the green packaging dimension. In our research, the green material dimension focuses on the source of raw materials for clothing and the utilization of materials [26, 27], firstly, identifying the source of raw materials for clothing fibres and accessories (sewing thread, button, zip, fabric tape, filling material, etc.), secondly, assessing the utilization of materials at the end of the clothing life cycle. This dimension reflects the characteristics of sustainable clothing (the use of environmentally friendly materials) and refers to 2 life cycle stages: the raw material extraction and production stage, and the end-of-life stage. The green design dimension focuses on the degree to which the design of the clothing's structure, style and fabric is compatible with sustainable design strategy [35]. This dimension reflects the characteristics of sustainable clothing (the application of sustainable design strategy); it is also the dimension that best reflects the characteristics of the clothing product. The green production dimension focuses on the

manufacturing capacity and processing level of clothing manufacturers [36, 37]. Firstly, assessing the manufacturing capacity, secondly, a large amount of waste material is generated during the clothing manufacturing process [37], which requires assessing the level of recycling and reuse of waste material. This dimension reflects the characteristics of sustainable clothing (efficient and clean production conditions) and refers to the life cycle stage of fabric weaving and clothing manufacturing. The green quality dimension focuses on the quality, functional, and economic attributes of clothing [38, 39], firstly, assessing the amount of product standard (E.g., OEKO-TEX, etc.) the clothing fulfils, secondly, assessing the comfort of clothing, and finally, assessing the production and

maintenance cost of clothing. This dimension refers to the life cycle stage of use and maintenance. The green packaging dimension focuses on the attributes of clothing packaging materials and packaging body [30]. This dimension reflects the characteristics of sustainable clothing (the use of environmentally friendly packaging) and refers to the life cycle stage of the end-of-life.

Establishment of the evaluation system

The clothing green degree evaluation system (5 indexes at first class, 11 indexes at second class, 27 indexes at third class) is established by reviewing related works in the previous section, as shown in table 1.

Table 1

THE CLOTHING GREEN DEGREE EVALUATION SYSTEM			
First-class index	Second-class index	Third-class index	Index interpretation and evaluation standards
Green material C ₁	Material sources C ₁₁	Usage rate of renewable raw materials C ₁₁₁	Ratio of renewable materials to fibre and accessory raw materials, the higher this ratio, the higher the green degree.
		Usage rate of recycled raw materials C ₁₁₂	Ratio of recycled materials to fibre and accessory raw materials, the higher this ratio, the higher the green degree.
		Usage rate of degradable raw materials C ₁₁₂	Ratio of degradable materials to fibre and accessory raw materials, the higher this ratio, the higher the green degree.
	Utilisation of materials C ₁₂	Quantity of material types C ₁₂₁	The quantity of fibre and accessory raw materials, the lower this quantity, the higher the green degree.
		Recyclability of materials C ₁₂₂	The proportion of resources that can be recycled and then processed for reuse after clothing is discarded. The higher this proportion, the higher the green degree.
		Reusability of materials C ₁₂₃	The proportion of resources that can be disassembled and reused directly after the garment is discarded. The higher this proportion, the higher the green degree
Green design C ₂	Structure and styling C ₂₁	The classical degree of clothing style C ₂₁₁	The style matches the classic design philosophy and avoids temporary fashions; the more classic the style, the higher the green degree.
		The degree of simplicity of the clothing pattern C ₂₁₂	The pattern should be simple, balancing the proportions of clothing and aiming for zero-waste design. The simpler the clothing pattern, the higher the green degree.
		Replaceability of clothing components C ₂₁₃	The degree of replaceability of clothing components, the higher this degree, the higher the green degree.
	Colour and texture C ₂₂	The degree of the original colour of clothing C ₂₂₁	Emphasis on the original colours of fabrics and accessories to reduce the hazards of dyes and auxiliaries, the higher the degree, the higher the green degree.
		The degree of the original texture of clothing C ₂₂₂	Emphasis on the original texture of fabrics and accessories to reduce unnecessary decoration and craftsmanship, the higher this degree, the higher the green degree.
Green production C ₃	Manufacturing capacity C ₃₁	Usage rate of energy-saving equipment C ₃₁₁	Ratio of energy-saving equipment used in manufacturing to total equipment; the higher this ratio, the higher the green degree.
		The level of green process technology C ₃₁₂	Levels of control and processing of noise, waste gas and wastewater during manufacturing, the higher this level, the higher the green degree.
		The level of the efficient manufacturing process C ₃₁₃	Levels of manufacturing workshop automation and manufacturing process simplification, the higher this level, the higher the green degree.
	Processing level C ₃₂	Technical level of waste material recycling C ₃₂₁	The technical level of recycling of trimmings, waste clothing patterns, leftover material, etc., for post-processing reuse, the higher this level, the higher the green degree.

Table 1 (continuation)

First-class index	Second-class index	Third-class index	Index interpretation and evaluation standards
		Technical level of waste material reuse C_{322}	The technical level of direct reuse of trimmings, waste clothing patterns, leftover material, etc., the higher this level, the higher the green degree.
Green quality C_4	Quality attributes C_{41}	Quality standard of clothing C_{411}	The level of product standards (E.g., OEKO-TEX, etc.) that the clothing can fulfil, the higher this level, the higher the green degree.
		Comfort of clothing C_{412}	Including thermal-wet comfort, fitness comfort, contact comfort, etc., the more conditions the clothing fulfils, the higher the green degree.
		Lifespan of clothing C_{413}	Including colour fastness, stability of fabric, contact durability of accessory, etc., the more conditions the clothing fulfils, the higher the green degree.
	Functional attributes C_{42}	Use the function of clothing C_{421}	Including essential use functions and other functions, the richer the function, the higher the green degree.
		Social function of clothing C_{422}	Including individual aesthetic, social status, and other social attributes that clothing can demonstrate, the richer the function, the higher the green degree.
	Economic attributes C_{43}	Production cost of clothing C_{431}	Including the cost of R&D, material, production, transport, storage, etc., the lower this cost, the higher the green degree.
		Maintenance cost of clothing C_{432}	The frequency of garment washing, dry cleaning, drying, ironing, etc., the lower the frequency, the higher the green degree.
Green packaging C_5	Packaging materials C_{51}	Sustainability of raw materials C_{511}	The more environmentally friendly the packaging material, the higher the green degree.
		Reusability of packaging C_{512}	The degree of direct reuse of the packaging, the higher this degree, the higher the green degree.
	Packaging body C_{52}	Ease of unpacking C_{521}	Packaging is designed to be as simple as possible, with less tape, glue, etc., to hinder disassembly and recycling. The easier the packaging is to disassemble, the higher the green degree.
		The degree of volume minimisation of packaging C_{522}	Provided there is enough packaging space for the clothing, the smaller the package volume, the higher the green degree.

We validated the third-class index through a questionnaire survey to ensure that they all describe the evaluation target. Applying the Likert 5-point Scale, we investigate the impact of 27 third-class indexes on the clothing green degree evaluation system, which requires at least 135 questionnaires [40]. A total of 255 people were interviewed, and they can be divided into two categories: 1) In-service teachers and graduate students of textile and fashion related majors (from Donghua University, Jiangnan University, Zhejiang Sci-Tech University, and Xi'an Polytechnic University); 2) Employees with textile and fashion product development experience of 3 years or more (from Guangdong Esquel Textiles Co., Ltd, Semir Group Co., Ltd, Anzheng Fashion Group Co., Ltd). A total of 232 valid questionnaires were collected, with an effective rate of 90.98%. Importing sampling data into SPSS 23.0, the overall Cronbach's α of the sampling data is $0.848 > 0.7$, the KMO is $0.837 > 0.6$, and the Sig. is $0.000 < 0.05$, which shows a good result. Then, we validated the value of α after deletion of the index and the CITC of the 27 indexes, as shown in table 2. The CITC of the 27 indexes were all

Table 2

DATA TESTING OF INDEX					
Index	α after deletion of index	CITC	Index	α after deletion of index	CITC
C_{111}	0.844	0.358	C_{321}	0.846	0.311
C_{112}	0.842	0.417	C_{322}	0.844	0.339
C_{113}	0.842	0.407	C_{411}	0.843	0.379
C_{121}	0.843	0.373	C_{412}	0.844	0.357
C_{122}	0.843	0.387	C_{413}	0.843	0.372
C_{123}	0.843	0.391	C_{421}	0.842	0.424
C_{211}	0.843	0.380	C_{422}	0.840	0.460
C_{212}	0.843	0.374	C_{431}	0.845	0.309
C_{213}	0.843	0.379	C_{432}	0.843	0.390
C_{221}	0.845	0.303	C_{511}	0.841	0.444
C_{222}	0.845	0.318	C_{512}	0.841	0.440
C_{311}	0.842	0.398	C_{521}	0.840	0.472
C_{312}	0.843	0.366	C_{522}	0.841	0.454
C_{313}	0.845	0.331			

higher than 0.3, and the values of α after deletion of the index were all lower than 0.848, indicating that deleting any index would reduce the credibility of the data. Thereby, all indices in the system are suitable for the description of the evaluation target.

METHODOLOGY

Method of weight calculation

The analytic hierarchy process (AHP) is limited by the singular characteristic of its evaluation scale, which cannot comprehensively represent the assessment results provided by experts. To further reduce the impact of ambiguity in expert evaluations on the accuracy of the results, we have introduced the concepts of fuzzy mathematics. TFN-AHP is a better weighting method that combines triangular fuzzy numbers with the analytic hierarchy process. Compared with the analytic hierarchy process, TFN-AHP establishes the fuzzy judgment matrix by introducing triangular fuzzy numbers, which can fully consider the influence of the ambiguity of expert judgments on the evaluation results [41].

Assume that the fuzzy set of the argument domain R in the interval $[0,1]$ is $\tilde{S}$, and its arbitrary map $\mu_{\tilde{S}} \in [0,1]$. Where, $\mu_{\tilde{S}}$ is the membership function of $\tilde{S}$, $\mu_{\tilde{S}}(x)$ is the degree of membership of the eigenvalue x to $\tilde{S}$, which can be expressed as a triangular function, as shown in equation 2:

$$\mu_{\tilde{S}}(x) = \begin{cases} 0, & x < l, x > u \\ \frac{x-l}{m-l}, & l \leq x \leq m \\ \frac{x-u}{m-u}, & m \leq x \leq u \end{cases} \quad (2)$$

where l and u are the upper and lower bounds of the fuzzy set $\tilde{S}$, respectively. m is the value for which the degree of membership of $\tilde{S}$ is 1. The triangular fuzzy number is denoted as $\tilde{S} = (l, m, u)$, let the two triangular fuzzy numbers be $\tilde{S}_i = (l_i, m_i, u_i)$, $\tilde{S}_j = (l_j, m_j, u_j)$, respectively, and the calculation rules are shown in equations 3 to equation 6.

$$\tilde{S}_i + \tilde{S}_j = (l_i, m_i, u_i) + (l_j, m_j, u_j) = (l_i + l_j, m_i + m_j, u_i + u_j) \quad (3)$$

$$\tilde{S}_i \times \tilde{S}_j = (l_i, m_i, u_i) \times (l_j, m_j, u_j) = (l_i \times l_j, m_i \times m_j, u_i \times u_j) \quad (4)$$

$$\varphi \tilde{S}_i = \varphi(l_i, m_i, u_i) = (\varphi l_i, \varphi m_i, \varphi u_i) \quad (5)$$

$$(\tilde{S}_i)^{-1} = [(l_i, m_i, u_i)]^{-1} = \left(\frac{1}{l_i}, \frac{1}{m_i}, \frac{1}{u_i} \right) \quad (6)$$

Compare the importance of all indexes in the same layer to generate the judgment result, which is expressed by the triangular fuzzy number and generate the judgment matrix $\tilde{C} = (\tilde{c}_{ij})_{n \times n}$, where $\tilde{c}_{ij} = (l_{ij}, m_{ij}, u_{ij})$, $\tilde{c}_{ji} = (\tilde{c}_{ij})^{-1}$. Judgment rule as shown in table 3.

Based on the judgment matrix $\tilde{C}$, calculate the fuzzy weight vector $\tilde{\omega}_i$ for the same layer of n indexes, as shown in equation 7.

Table 3

LINGUISTIC VARIABLES AND TRIANGULAR FUZZY NUMBERS WITH QUANTITATIVE SCALES		
Linguistic terms	Fuzzy number	Triangular fuzzy number
Equally important	1	(1, 1, 1)
Moderately more important	3	(2, 3, 4)
Strongly more important	5	(4, 5, 6)
Very strong more important	7	(6, 7, 8)
Extremely more important	9	(8, 9, 9)
Intermediate values	2, 4, 6, 8	Between the values above

$$\tilde{\omega}_i = \frac{\sum_{j=1}^n \tilde{c}_{ij}}{\sum_{k=1}^n \sum_{j=1}^n \tilde{c}_{ij}} = \left(\frac{\sum_{j=1}^n l_{ij}}{\sum_{j=1}^n l_{ij} + \sum_{k=1, k \neq i}^n \sum_{j=1}^n u_{kj}}, \frac{\sum_{j=1}^n m_{ij}}{\sum_{k=1}^n \sum_{j=1}^n m_{kj}}, \frac{\sum_{j=1}^n u_{ij}}{\sum_{j=1}^n u_{ij} + \sum_{k=1, k \neq i}^n \sum_{j=1}^n l_{kj}} \right) \quad (7)$$

To performing the consistency checking on $\tilde{C}$, a non-fuzzy judgment matrix C needs to be formed using m_{ij} , and then the consistency checking is performed on the matrix C .

Firstly, calculate the weight vector ω_i after normalizing the n row vectors of the matrix C , as shown in equation 8.

$$\omega_i = \left(\frac{\sum_{j=1}^n m_{ij}}{\sum_{j=1}^n \sum_{k=1}^n m_{ij}} \right)^T \quad (8)$$

Secondly, calculate the maximal characteristic root λ_{max} of the matrix C , as shown in equation 9.

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^n \frac{\sum_{j=1}^n c_{ij} \omega_j}{\omega_i} \quad (9)$$

Thirdly, calculate the consistency checking index CI , then combine it with the random consistency index RI to calculate the CR , where $CI = (\lambda_{max} - n) / (n - 1)$, $CR = CI / RI$. The matrix C passes the consistency checking if $CR < 0.1$. After passing the consistency checking, the fuzzy weight vector of each index in the judgment matrix is performed Monte Carlo simulation, which achieves defuzzification and obtains the weights of each index. We performed a Monte Carlo simulation by using the triangular distribution function, which is shown in equation 10:

$$f(x|a, b, c) = \begin{cases} \frac{2(x-a)}{(b-a)(c-a)}, & a \leq x \leq c \\ \frac{2(x-b)}{(b-a)(c-b)}, & c \leq x \leq b \end{cases} \quad (10)$$

where a , b , and c are the lower limit value, the upper limit value, and the mode number, respectively, which together form the continuous probability density function. According to equation 10, the fuzzy weight was transformed into the form of the triangular distribution function, and then a Monte Carlo simulation was carried out to generate several random sets of sample

data, and the mode number of these sample data was the index weight. The weight of each index is synthesised according to the layer to form the synthetic weight $W_i^{(e)}$ of each index for the target layer, as shown in equation 11:

$$W_i^{(e)} = \prod_{e=1}^{n-1} w_i^{(e)} \quad (11)$$

where $i = 1, 2, \dots, n$, $w_i^{(e)}$ is the weight of the i -th index at layer e . $W_i^{(e)}$ is the synthetic weight of the i -th index at layer e for the target layer.

Method of evaluation model establishment

Clothing green degree evaluation indexes have the characteristics of a large number, a wide range, and low measurability, which leads to an unknown degree of impact among the indexes. thereby, we use the grey clustering method to establish the evaluation model. Grey clustering method quantifies the similarity of evaluation data using the whitening weight function to achieve rank classification, which is suitable for evaluation systems with a small sample size and clear grade.

To achieve better evaluation results, the green degree evaluation usually divides the grade into 5 levels [32], thereby, we divide the clothing green degree into 5 evaluation grades: dark green, green, quasi-green, light green and grey, and assign scores of 5, 4, 3, 2 and 1 to form the grey class grade vector. Z experts are invited to establish the grey evaluation matrix by scoring the grades of evaluation indexes $C_{111}-C_{522}$. Then we established the valued vector $V = (v_1, v_2, v_3, v_4, v_5) = (5, 4, 3, 2, 1)$ based on the 5 evaluation grades, and established the whitening weight function f_j^S for the K^{th} grey class corresponding to the j -th index, as shown in figure 2, where $j = 1, 2, \dots, 27$; $K = 1, 2, 3, 4, 5$.

For any third-class index C_{rst} of the evaluated target, the corresponding score $h_{C_{rst}}^v$ and the grey evaluation weight $q_{C_{rst}}^k$ of the K^{th} grey class is shown in equation 12, where $k = 1, 2, 3, 4, 5$:

$$q_{C_{rst}}^k = \frac{\sum_{v=1}^Z f^K(h_{C_{rst}}^v)}{\sum_{K=1}^5 \sum_{v=1}^Z f^K(h_{C_{rst}}^v)} \quad (12)$$

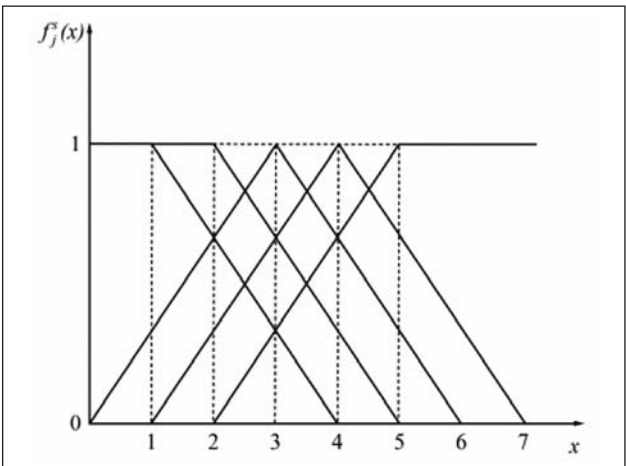


Fig. 2. Whitening weight function for 5 types of grey classes

where $f^K(h_{C_{rst}}^v)$ is the whitening weight coefficient of the K^{th} grey class judged by the expert. $h_{C_{rst}}^v$ is the evaluation grade of the v^{th} expert on the third-class index. By calculating the grey evaluation weight of each index, the grey evaluation weight matrix $Q_{C_{rs}} = (q_{C_{rs}1}, q_{C_{rs}2}, \dots, q_{C_{rs}y})^T$ can be obtained, as we can perform the comprehensive evaluation. The grey evaluation weight matrix of each index at the layer of third-class index can be used to obtain the grey evaluation weight matrix Q_{C_r} of each index at the layer of second-class index, and then the comprehensive evaluation result G_i at the layer of first-class index and the final comprehensive evaluation result G can be obtained, as shown in equations 13 to 14.

$$G_i = W_{C_{rs}} Q_{C_r} = (g_i^1 g_i^2 g_i^3 g_i^4 g_i^5) \quad (13)$$

$$G = W_{C_r} Q = (g_1 g_2 g_3 g_4 g_5) \quad (14)$$

where $W_{C_{rs}}$ is the weight of the index at the layer of the second-class index. W_{C_r} is the weight of the index at the layer of the first-class index. The result of the evaluation grade can be obtained according to the maximum membership degree principle, and the result of the evaluation score can be obtained according to the vector V .

RESULTS

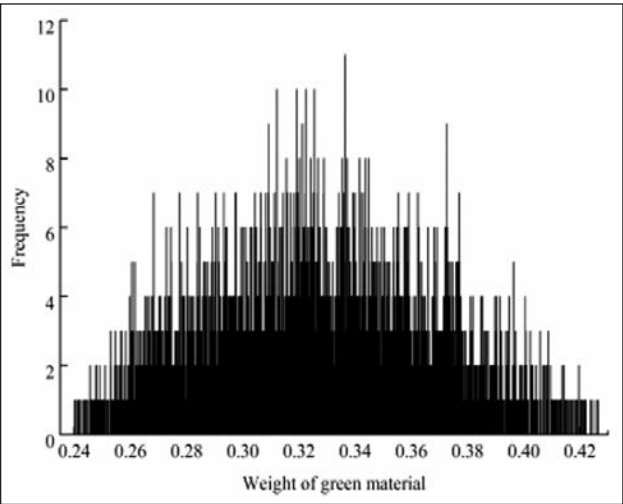
Results of index weight

We invited 8 textile and fashion-related professional teachers with 10 years or more work experience (1 from Donghua University, 1 from Jiangnan University and 6 from Xi'an Polytechnic University) and 3 fashion company employees with 10 years or more working experience (1 from Guangdong Esquel Textiles Co., Ltd and 2 from Semir Group Co., Ltd) to score the evaluation index. A total of 17 sets of fuzzy judgment matrix were generated according to table 3 and equations 3–6, and the weight vector of each index in the fuzzy judgment matrix of each layer can be calculated according to equation 7. We took the layer of the first-class index as an example, as follows.

$$\tilde{\omega}_{C_i} = \begin{bmatrix} (0.2379, 0.3259, 0.4281) \\ (0.0636, 0.0979, 0.1493) \\ (0.2779, 0.3762, 0.4819) \\ (0.1026, 0.1569, 0.2298) \\ (0.0319, 0.0431, 0.0638) \end{bmatrix}$$

The m_{ij} of the fuzzy judgment matrix $\tilde{C}_{C_i}$ was used to establish the 5-order matrices ($R/I=1.12$), which leads to the consistency checking of the non-fuzzy judgment matrix. The weight vector of the non-fuzzy judgment matrix is calculated as $\omega = (0.3259, 0.0979, 0.3762, 0.1569, 0.0431)$ by equation 8, and the λ_{max} is calculated as 5.1519 by equation 9; thereby, the CR is $0.0339 < 0.1$, which means the matrix passes the consistency checking. Then, firstly, we converted the weight vectors of C_1-C_5 into a triangular distribution function, which, in the case of C_1 , is $f_{C_1}(x_{C_1}|a_{C_1}, b_{C_1}, c_{C_1}) = f(x_{C_1}|0.2379, 0.3259, 0.4281)$. Secondly, we combined equation 10 for Monte Carlo

simulation, and performed 5000 random sampling on the triangular distribution function of C_1 - C_5 to obtain the weight frequency figures, and the figures show that the weights are 0.3364, 0.0935, 0.3689, 0.1556, 0.0456. Take C_1 as an example, as shown in figure 3.



By following the steps above, the weights of C_{11} - C_{52} , C_{111} - C_{522} and the synthetic weights were calculated, as shown in table 4; all indexes in this evaluation system pass the consistency checking.

Application of the evaluation model

To verify the accuracy of the evaluation index and its model, we selected a Men’s POLO shirt of a brand in spring 2022 for green degree evaluation, as shown in table 5. This shirt is positioned by the brand as sustainable clothing; thereby, if this shirt achieves the grade of quasi-green or above, it shows that the shirt is indeed sustainable clothing, and the accuracy of the evaluation index and its model is also verified. We investigated the source of raw material, design detail, production equipment, process technology, workshop environment, storage cost, packaging, etc. of this shirt, then we invited 5 experts (3 teachers from Xi’an Polytechnic University with senior titles and 2 engineers from China Textile Planning Institute of Construction with senior titles) to rate this shirt. Then, we calculated the value of the whitening weight

Table 4

INDEX WEIGHTS AND THE CONSISTENCY CHECKING								
Layer of first-class index		Layer of the second-class index			Layer of the third-class index			
Index	Weight	Index	Consistency checking	Weight	Index	Consistency checking	Weight	Synthetic weight
C ₁	0.3364	C ₁₁	$\lambda=2, n=2$ $CI=CR=0$	0.5565	C ₁₁₁	$\lambda=3.0059, n=3$ $CI=0.0030$ $CR=0.0051$	0.2558	0.0479
					C ₁₁₂		0.4214	0.0789
					C ₁₁₃		0.3228	0.0604
		C ₁₂		0.4435	C ₁₂₁	$\lambda=3.0363, n=3$ $CI=0.0181$ $CR=0.0313$	0.1491	0.0222
					C ₁₂₂		0.3965	0.0592
					C ₁₂₃		0.4544	0.0678
C ₂	0.0935	C ₂₁	$\lambda=2, n=2$ $CI=CR=0$	0.3318	C ₂₁₁	$\lambda=3.0046, n=3$ $CI=0.0023$ $CR=0.0039$	0.3717	0.0115
					C ₂₁₂		0.3212	0.0100
					C ₂₁₃		0.3071	0.0095
		C ₂₂		0.6682	C ₂₂₁	$\lambda=2, n=2$ $CI=CR=0$	0.7444	0.0465
					C ₂₂₂		0.2556	0.0160
C ₃	0.3689	C ₃₁	$\lambda=2, n=2$ $CI=CR=0$	0.5929	C ₃₁₁	$\lambda=3.0029, n=3$ $CI=0.0014$ $CR=0.0025$	0.3598	0.0787
					C ₃₁₂		0.3295	0.0721
					C ₃₁₃		0.3107	0.0679
		C ₃₂		0.4071	C ₃₂₁	$\lambda=2, n=2$ $CI=CR=0$	0.4806	0.0722
					C ₃₂₂		0.5194	0.0780
C ₄	0.1556	C ₄₁	$\lambda=3.0162, n=3$ $CI=0.0081$ $CR=0.0140$	0.4174	C ₄₁₁	$\lambda=3.0228, n=3$ $CI=0.0114$ $CR=0.0197$	0.4612	0.0300
					C ₄₁₂		0.3078	0.0200
					C ₄₁₃		0.2310	0.0150
		C ₄₂		0.2578	C ₄₂₁	$\lambda=2, n=2$ $CI=CR=0$	0.6950	0.0279
					C ₄₂₂		0.3050	0.0122
		C ₄₃		0.3248	C ₄₃₁	$\lambda=2, n=2$ $CI=CR=0$	0.5345	0.0270
C ₄₃₂	0.4655		0.0235					
C ₅	0.0456	C ₅₁	$\lambda=2, n=2$ $CI=CR=0$	0.6738	C ₅₁₁	$\lambda=2, n=2$ $CI=CR=0$	0.4712	0.0145
					C ₅₁₂		0.5288	0.0162
		C ₅₂		0.3262	C ₅₂₁	$\lambda=2, n=2$ $CI=CR=0$	0.4036	0.0060
					C ₅₂₂		0.5964	0.0089

PRODUCT INFORMATION FOR THE MEN'S POLO SHIRT			
			Type: Men's POLO shirt Standard: GB/T 14272-2011 Safety category: GB18401-2010 Type B Grade: First class

function for each evaluation index for each of the 5 grey classes separately according to figure 2, then, we established the grey evaluation weight matrix for each index according to equation 12, then, we performed the comprehensive evaluation of C_{11} - C_{52} and then we calculated the grey evaluation weight matrix Q_{C_1} - Q_{C_5} for C_1 - C_5 according to the grey evaluation weight matrix, as follows.

$$Q_{C_1} = \begin{bmatrix} 0.2820 & 0.3153 & 0.2508 & 0.1176 & 0.0343 \\ 0.2149 & 0.2989 & 0.2789 & 0.1555 & 0.0517 \end{bmatrix}$$

$$Q_{C_2} = \begin{bmatrix} 0.2140 & 0.2844 & 0.2739 & 0.1629 & 0.0648 \\ 0.1313 & 0.2456 & 0.3141 & 0.2117 & 0.0974 \end{bmatrix}$$

$$Q_{C_3} = \begin{bmatrix} 0.3279 & 0.3176 & 0.2334 & 0.0931 & 0.0281 \\ 0.2564 & 0.3333 & 0.2564 & 0.1282 & 0.0256 \end{bmatrix}$$

$$Q_{C_4} = \begin{bmatrix} 0.3078 & 0.3093 & 0.2426 & 0.1050 & 0.0356 \\ 0.3053 & 0.3226 & 0.2407 & 0.1042 & 0.0273 \\ 0.2863 & 0.2919 & 0.2541 & 0.1190 & 0.0487 \end{bmatrix}$$

$$Q_{C_5} = \begin{bmatrix} 0.2972 & 0.3243 & 0.2433 & 0.1082 & 0.0270 \\ 0.3157 & 0.3203 & 0.2373 & 0.0991 & 0.0276 \end{bmatrix}$$

Based on the above results, we calculated the comprehensive evaluation result G_1 - G_5 according to **equation 13**, which can be used to calculate the grey evaluation weight matrix Q , as follows.

$$Q = \begin{bmatrix} 0.25220 & 0.30800 & 0.26330 & 0.13440 & 0.0420 \\ 0.15870 & 0.25840 & 0.30080 & 0.19550 & 0.0866 \\ 0.29880 & 0.32400 & 0.24280 & 0.10740 & 0.0271 \\ 0.30020 & 0.30690 & 0.24590 & 0.10930 & 0.0377 \\ 0.30320 & 0.32300 & 0.24130 & 0.10520 & 0.0272 \end{bmatrix}$$

Based on the grey evaluation weight matrix Q and equation 14, we calculated the final comprehensive evaluation result G , $G = [0.2704, 0.3098, 0.2555, 0.1249, 0.0393]$.

Based on the final comprehensive evaluation result G and the maximum membership degree principle, we judged that this shirt was evaluated as a 'green' grade, and we calculated the comprehensive evaluation score of this shirt is 3.6470 according to the valued vector V .

DISCUSSION

Contribution and limitation

According to the evaluation results, the Men's POLO shirt was rated as 'Green' grade, indicating a high

level of sustainability that aligns with its actual properties. This outcome validates the clothing green degree evaluation framework, demonstrating its critical role in determining results and its applicability for evaluating the environmental sustainability of apparel. Furthermore, clothing is different from general textile products, and there is a lack of related works on sustainable evaluation based on clothing characteristics, which also provides us with a certain research opportunity. Thereby, we introduced the green degree evaluation, whose core evaluation dimensions are environmental friendliness, technological advancement, and economic rationality. Based on this theory, the clothing green degree evaluation system and evaluation model are established, which consists of green material, green design, green production, green quality, and green packaging to evaluate the environmental sustainability of clothing. This evaluation framework provides a robust measure of the environmental sustainability of clothing, offering a novel approach for related research, moreover, the effective application of the TFN-AHP and grey clustering methods was instrumental in its development.

A primary limitation of this study is that the proposed framework is tailored for common clothing; it does not encompass the environmental sustainability evaluation of special-purpose clothing. Evaluating such products would necessitate the development of a dedicated framework.

The clothing green degree evaluation system aims to reflect the product characteristics of clothing and aims to distinguish it from general textile products, which is also the highlight of our research. Thereby, from the perspective of clothing products, using the index in our work to evaluate the clothing green degree can minimise the deviation of evaluation results and facilitate practical operation.

Practical suggestion

Among the 5 evaluation dimensions of the clothing green degree evaluation system, green production and green material have a higher weight, accounting for 36.89% and 33.64% respectively. Although our research is based on China and represents the views of some experts in the field of textile and fashion in China, achieving sustainable production is still a

problem that needs to be solved in the textile and clothing industry of most countries in the world [2, 42]. Both efficient and clean production conditions and the sustainability of raw materials represent the sustainable production and R&D level of the clothing enterprise. Thereby, the improvement of the clothing sustainability still requires the clothing enterprise to use advanced equipment, develop environmental friendly technology, simplify manufacturing processes, and make effective use of waste materials, which can effectively reduce the emission of waste gas, wastewater and other pollutants during the production of clothing, and allocate these environmental benefits to each piece of clothing, which can significantly improve the sustainable level of clothing. Although improving the level of green production will cause significant financial pressure on textile and garment enterprises in the early stage, it also means higher production efficiency, lower production costs, a cleaner production environment and environmentally friendly products in the future. At present, relevant government departments and financial institutions are vigorously promoting green finance, and it is suggested that textile and apparel enterprises flexibly combine different green financial products according to their own needs to finance in stages, gradually improving the level of green production. In addition, with the awakening of sustainable consumption awareness, in the future, clothing with a high green degree will be favoured by consumers, and enterprises with higher levels of green production will have a broader market.

CONCLUSION

This study develops the clothing green degree evaluation system based on the concept of green degree

evaluation and employs the TFN-AHP and grey clustering method to develop a corresponding evaluation model. The main conclusions are summarised as follows:

- The green degree evaluation serves as a practical tool for evaluating the environmental sustainability of clothing. Based on the evaluation principles of environmental friendliness, technological advancement and economic rationality, the clothing green degree evaluation system, established from 5 dimensions of green materials, green design, green production, green quality, and green packaging, can comprehensively describe the environmental sustainability of clothing.
- TFN-AHP and grey clustering methods are well-suited for application within the clothing green degree evaluation model. While the proposed clothing green degree evaluation framework demonstrates practical value, the refinement of evaluation criteria and further improvement of the evaluation methodology warrant additional investigation.
- Among the 5 first-class indexes of the clothing green degree evaluation system, green production and green material have a greater weight on green degree, accounting for 36.89% and 33.64% respectively, followed by green quality, green design, and green packaging. The clothing R&D plan can be formulated according to the indexes with larger weights in this evaluation system, to guide production and product classification.

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