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Review

The Status Quo and Prospect of Sustainable Development of Smart Clothing

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Abstract: With the booming development of the Internet and AI (Artificial Intelligence), smart clothing has emerged to meet consumers' personalized needs in healthcare, work, entertainment, etc., and has rapidly become a hotspot in the clothing industry and research field. However, as smart clothing gets popular, sustainability issues are becoming increasingly prominent during its development and circulation. To explore the status quo of the sustainable development of smart clothing, from the perspective of the industry chain, this paper discusses its challenges during raw material supply, design, manufacturing, storage, logistics and recycling. Based on these challenges and the characteristics of smart clothing and the future trend of the apparel industry, some countermeasures are put forward from three aspects: design, raw material and supply chain management. This review aims to arouse the reflection of practitioners and provide feasible suggestions for the healthy and lasting development of the apparel industry, also hoping to offer references for other industries.

Keywords: smart clothing; sustainability; design; production; supply chain

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1. Introduction

As science and technology progress, personalized products appear and gain favor. Consumers' high demand for the convenience and functionality of daily necessities makes them more intelligent. As a daily necessity, clothing not only plays the role of covering and warming but also gets more comfortable, functional and personalized. In addition, as a common technology carrier, clothing can be well integrated with intelligent technologies to build a human–computer interaction bridge [1]. The advent of the knowledge economy speeds up the development of electronic information technology so as to accelerate the emergence of smart clothing.

Smart clothing refers to clothing that is enhanced with technology to add functionality beyond the traditional use, capable of perception and response to mimic the characteristics of the life system [2]. Based on data processing, it is widely applied in the fields of exercise [3], medicine [4], military [5], entertainment [6], etc. The development of smart clothing involves multiple disciplines such as fashion design, textile technology, biology, informatics and marketing [7]. At present, its various functions (e.g., positioning, alarm, physiological monitoring and interaction) are mainly realized in two ways. The first one is to build in electronic components. For example, French company In&motion developed an intelligent vest for skiers, which had a built-in GPS, gyroscope, accelerometer and other sensors [8]. The iTBra smart bra developed by Cyrcadia Health can perform an early screening of breast cancer by using an integral thermosensitive sensor [9]. With the progress of materials and information technologies, a softer intelligent way emerged: converting electronic components into textile materials, which alleviates the problem that the functional components are too bulky and rigid. For example, Siren Socks (smart socks) were integrated with temperature sensors to help diabetics prevent diabetic foot [10]. Sensors, heating coils and clothes were weaved together in the intelligent constant temperature clothing developed by Clim8, effectively improving the wearing comfort [11]. Nowadays, new media are improving public aesthetics. Apart from functionality, consumers have higher requirements for the appearance of smart clothing. Therefore, the balance of aesthetics and functionality should be emphasized so as to meet the physiological and psychological needs of consumers [12]. It is predicted that more advanced technologies will be integrated into smart clothing in the future.

As a new concept and strategy, sustainable development has been widely concerned with all walks of life. Recently, consumers' pursuit of fashion trends has aggravated overproduction in the garment industry [13], which has led to resource waste, environmental pollution and ecological imbalance. As a frontier technology, smart clothing has encountered some obstacles to sustainable development. The traditional fashion design concept, market interests and consumers' attitude have affected the sustainability of intelligent clothing. Therefore, although problems such as environmental deterioration and resource shortage have caused some positive responses from garment enterprises, most enterprises are still at the elementary stage of exploration.

The clothing supply chain includes raw material procurement, design, manufacturing, transportation, sales and recycling [14]. With the addiction of electronic technology, the procedures in all links of the intelligent clothing supply chain are more complex than ordinary clothing, resulting in more environmental problems such as carbon emission, water pollution, metal pollution, etc. For example, the nonbiodegradability of metal materials can easily lead to soil pollution and chemical pollution, affecting the secondary utilization of materials [15]. In addition to the environmental pressure brought by the supply chain, the lack of consumers' concept of sustainable consumption is also a major factor affecting the healthy development of smart clothing. At present, the environmental issues caused by the apparel industry are not only limited to technology but also related to consumers' consciousness [16]. Moreover, the immaturity of wearable technology, short service life [17] and low utilization [18] make its life cycle shorter than that of ordinary clothing, which accelerates raw material loss and waste textile accumulation.

The lack of sustainability of smart clothing has increased the pressure on the environment, society and economy and is not conducive to maintaining the vitality of the apparel industry. Therefore, fashion designers, manufacturers, sellers and consumers should perform a comprehensive review and reflection to carry out technological innovation and policy reform to implement sustainable development.

Currently, very few studies have been conducted to assess the challenges and implications of the sustainability of smart clothing. This review discusses smart clothing based on the sustainable development concept to achieve the following research objectives:

RO1. Clarify the concepts and influencing factors of sustainable fashion.

RO2. Recognize the existing challenges of sustainability in smart clothing.

RO3. Provide suggestions and exploration directions for the sustainable development of smart clothing.

The remaining article is organized as follows: Section 2 outlines the framework of the article. Section 3 defines the concept of sustainable fashion and investigates the main factors influencing it from a general point of view. Then, Section 4 introduces smart clothing and analyzes the challenges and suggestions for the sustainable development of smart clothing from the perspective of the industry chain. Finally, a conclusion is drawn in Section 5.

2. Research Framework

The research framework is depicted in Figure 1. It is mainly divided into two parts: (1) sustainable development and fashion and (2) sustainable development and smart clothing. The first part discusses the definition of sustainable development and sustainable fashion, exploring the role of the fashion industry in promoting global sustainable development. Next, the influencing factors of sustainable fashion are discussed from three aspects: design, social environment and commercial value. The second part is the key section, which discusses the relationship between sustainable development and smart clothing. During this part, the related concepts and characteristics of smart clothing are introduced, and the design principles of intelligent clothing are emphatically analyzed. Next, the existing limitations of the sustainable development of smart clothing are summarized from three aspects: environmental friendliness, life cycle and market circulation efficiency. Finally, some suggestions are put forward based on the limitations and future trends of the apparel industry. The suggestions are presented from three aspects: design, raw material and supply chain so as to provide some directions for the healthy and lasting development of the fashion industry in the future.

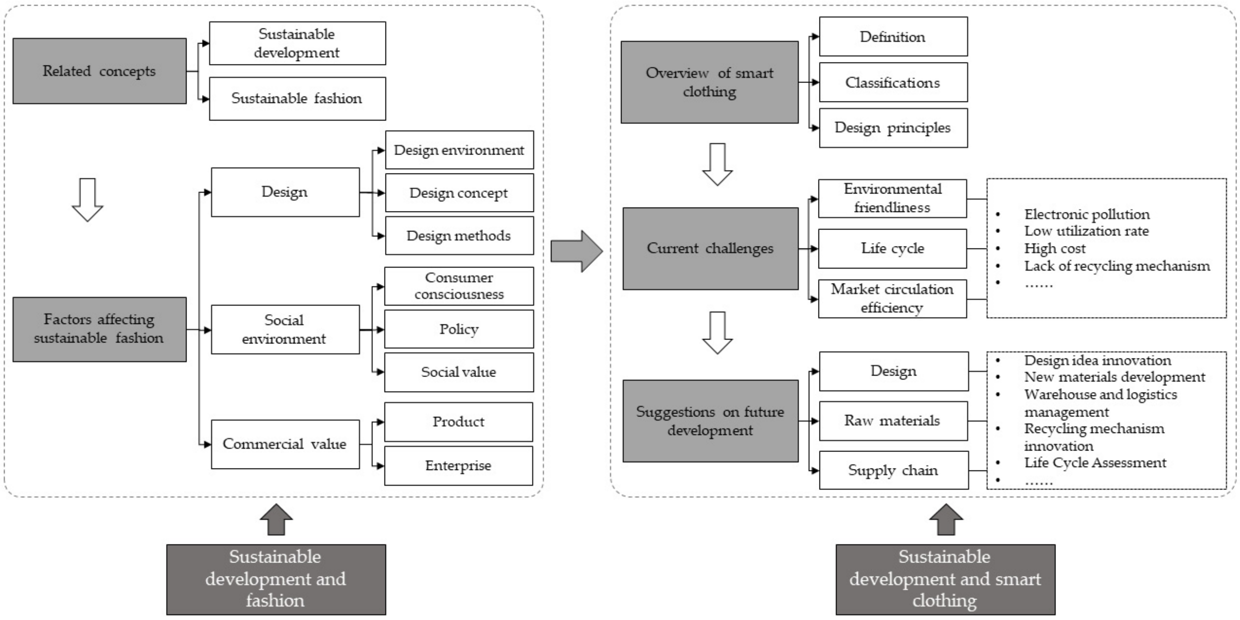

Figure 1. Research framework.

3. Sustainable Fashion

This part focuses on the concept of sustainable development and its relationship with the fashion industry. By clarifying the meaning of sustainable development in other fields, the definition of sustainable fashion and the role of fashion in promoting sustainable development are explained. On this basis, the influencing factors of sustainable fashion are discussed from the perspectives of design, social environment and commercial value.

3.1. Concept of Sustainable Development and Fashion

The threat of an ecological crisis to human survival brought up the concept of sustainable development. The highly recognized definition of sustainable development was put forward in the report issued by Brundtland [19] at the World Commission on Environment and Development in 1987, "Sustainable development is the development mode that meet the need of the present generation without compromising the ability of future generations to meet their own needs". Different fields have different understandings of sustainable development. Ecologists believe that sustainability is to seek an optimal ecosystem to ensure ecological integrity and the realization of human aspirations [20]. From the perspective of sociology, sustainable development refers to improving the quality of human life on the basis of not exceeding the capacity of the ecosystem [21]. Economists believe that sustainable development is an economic mode without sacrificing environmental quality and natural resources [22].

The Green Strategy Organization defines sustainable fashion as manufacturing, selling and wearing clothing, shoes and accessories in a sustainable way, taking into account the environmental and socio-economic impact during the processes [23]. Generally, clothing sustainability can be divided into two forms: clothing life cycle sustainability and design sustainability. Life cycle sustainability means that environmental friendliness and human friendliness will be achieved during fabric selection, manufacturing, marketing, using and recycling [24]. Design sustainability includes recycling and redesign of waste textiles [25]. For example, washable intelligent clothing that can also be disassembled reflects the concept of sustainable design. Overall, sustainable development of clothing is to balance economic development, environmental friendliness, clothing function and style modeling in order to provide comfortable, healthy and environment-friendly products under the principle of sustainable development.

3.2. Necessity of Sustainable Fashion

Fashion changes rapidly, partly as a result of individuals' desire to join larger social groups [26]. Clothing is regarded as an ideal choice to express personality and desire. Consumers need various garments to express themselves and integrate into a group, but they rarely consider the source, production and destination of clothes [27].

Fashion provides a variety of products to satisfy multiple requirements of consumers. However, in the long run, it brings a heavy burden to the ecological environment. The fashion industry is trapped in a vicious cycle where more and more shoddily made products appear and are quickly discarded, resulting in environmental pollution and resource consumption at a multiplying rate [26]. According to statistics, about a truck-load of fabric is piled up in the landfill every second, which means 7.6 to 10 cubic meters of textiles are dumped or burned every second. Additionally, the fashion industry causes about 1.2 billion greenhouse gas emissions every year and 500,000 tons of microfiber (equivalent to 5000 plastic bottles), leading to marine pollution [28]. Fletcher [29], founder of "slow fashion", argued in 2007 that the fashion industry had been disconnected from the practical issues. She argued that the fashion industry contributes to inequality, labor exploitation, resource waste, waste generation and environmental degradation and needs to be directed toward sustainability. In terms of ecological problems, the significance of sustainability is to make the fashion industry improve economic benefits, consumers' quality of life and the healthy development of the whole industry while having the lowest impact on the environment.

Clothing is a product that protects and expresses the needs of its wearer. Sustainable development adheres to the principle of "people-oriented", that is, puts a priority on consumers' needs, which requires designers to continuously improve and innovate design methods on the basis of the original functionality of clothing. With the increase of market demands for smart clothing, improving the sustainability of intelligent clothing can not only gain praise and favor from consumers but also promote the development of smart clothing into a healthy and scientific direction.

In a word, sustainability has an important impact on the fashion industry. On the one hand, it well reflects the harmonious relationship between human and nature and shows that the fashion industry is willing to promote the healthy development of society and nature. On the other hand, sustainable development can not only achieve ecological and environmental protection but also fully consider the long-term interests of enterprises, enabling enterprises to get a win-win situation of interests and reputation on the basis of consumer demands. Therefore, the implementation of sustainable development is very necessary for the fashion industry, which is of great practical significance to promote the healthy development of society and the environment.

3.3. Factors Affecting Fashion Sustainability

This section discusses the main factors affecting sustainable fashion development from three aspects: design, commercial value and social environment (Figure 2). These factors represent the three roles that form and influence fashion: designer, enterprise and society. The discussion on the influencing factors of fashion sustainability lays a foundation for discovering the challenges and opportunities of smart clothing on sustainable development.

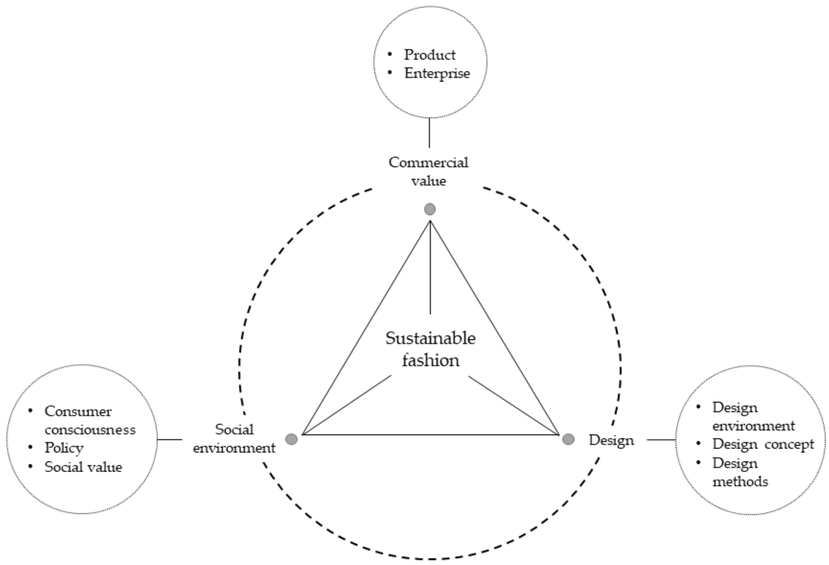

Figure 2. Factors affecting sustainable fashion.

3.3.1. Design

In the context of global climate change, sustainable design is getting popular in recent years. Sustainable design originated from the concept of sustainable development and was proposed at the end of the 20th century [30]. It comprehensively considers the economy, environment and society, aiming to guide and meet consumers' continuous demand [26]. Sustainable clothing design is to reduce pollution in the whole life cycle and realize the sustainable development of the environment and resources in a systematic way [30]. The reason why design is paid increasingly more attention is that designers' focus has shifted from remedy to prevention [31]. The following presents how design affects the sustainable development of the fashion industry from three angles: design environment, design concept and design methods.

As the background of garment production, the design environment exerts an imperceptible influence on designers. Only in a reasonable design environment may more designers willingly shoulder their responsibilities of sustainable development and incorporate it into specific designs [32]. The acts of fashion designers can drive other practitioners to actively participate in sustainable fashion. In addition, sustainable design embodies a new social culture, which will inevitably affect the design environment.

The development of design is driven by commercial interests all the time, partly because people lay more emphasis on market value than social functions. When designers are drawn into the business model, their aesthetic concept is shifted to the design goal of pursuing appearance, which makes it easy to guide consumers to carry out conspicuous consumption or be keen on the stimulation of aesthetic pleasure. The establishment of the sustainable design concept is the reconstruction of designers' value, culture and design concept, as well as a kind of social construction, which affects the consumers' behaviors and consumption concept and helps to improve their consciousness to the sustainable development of the fashion industry in the future.

Most designers tend to be obsessed with some specific aspect when considering sustainable design, thus ignoring the scientificity of the production process, the rationality and adaptability of functions and the long-term impact on the environment and society, etc. Designers should take existing technology, materials and other conditions into account and carry out reasonable clothing design so as to create truly sustainable products. Rational design methods are beneficial to reduce pollution in subsequent procedures, stimulate consumption in a novel and healthy way and promote the benign development of the apparel industry.

3.3.2. Social Environment

To achieve sustainable development, apart from the fashion product, the complex and changeable social environment should also be considered as the three components of social environment, government, enterprise and individual are closely related to the sustainable development of the fashion industry.

Consumers are the service objects, and their consumption concept directly affects the sustainable development of the fashion industry. Although sustainable development has been emphasized and governments have been required to respond positively, it is questionable whether the public is willing to sacrifice personal interests to promote sustainable development. Joung et al. [33] conducted a study among American women students majoring in textile and clothing and found that even in the social environment advocating recycling, young consumers still choose to dispose of unwanted clothes by discarding them. Blindly encouraging and advocating the role of promoting sustainable fashion development is far from enough. In fact, consumers pay more attention to commodities. The quality of a product will be fully reflected in the process of consumer use. The fashion industry should find effective measures to change consumers' attitude toward sustainable fashion and stimulate their active consumption.

To achieve sustainable fashion development, in addition to arousing public awareness of social responsibility, the implementation of policies should also be emphasized to put sustainable clothing production and consumption behavior into practice. In order to reduce the impact of clothing on society and the environment, many social responsibility policies have been formulated [34], and a rising number of clothing enterprises have actively participated in activities related to sustainable development. However, most of the existing policies only focus on a certain part of garment production (e.g., the selection of raw materials, the treatment of production sewage); thus formulating and implementing reasonable and comprehensive policies are necessary for the sustainable development of the fashion industry in the future.

Most traditional social values only recognize the value of nature to human beings but ignore the value of nature itself, which leads to the sharp contradiction between human and nature. Clothing consumers usually pay little attention to how clothing is produced, where discarded clothing goes and whether disposed-of clothing has an adverse impact on the social environment, while they pay more attention to whether clothing meets their personal needs. Therefore, the correct guidance of social values is significant for realizing the sustainable development of the apparel industry. Once consumers change their traditional ideas and establish a new consumption concept, a lasting and eternal driving force for sustainable fashion development will be provided. In addition to consumers, the concept of sustainable development can also serve as the companies' competitiveness. In 2008, Levi [34] launched an initiative to improve consumers' awareness of sustainable consumption and promote the healthy development of the company by displaying the life cycle assessment results of clothing to consumers.

3.3.3. Commercial Value

Commercial value affects the production quantity, target market scope, enterprise income and brand awareness [35]. Due to the large number of stakeholders, commercial value is the primary concern around sustainable development [36]. Enterprise is the provider of services and the principal part of market operation. For a long time, most enterprises have been taking the maximization of shareholders' interests as the operational goal and regarding sustainable development as an additional burden. However, the fact is that the business essence of sustainable development is to help enterprises balance the internal and external or long-term and short-term interests within limited resources so as to maximize organizational interests [37].

The sustainability of garments requires that the value should be maximized after products are put into the market. Only when the functionality and sustainability of clothing are combined perfectly can the significance of this product be reflected. Great clothing value is embodied in improving companies' core competitiveness and encouraging managers to change their business mode and truly integrate the concept of sustainable development into enterprise operation. Only in this way can they create long-term stakeholder interests and ensure steady improvement of profitability. In the long run, it is conducive to promoting the lasting development of the apparel industry.

4. Overview of Smart Clothing

4.1. Definition of Smart Clothing

Smart clothing can be defined as the intelligent system that senses and reacts to the changes and stimuli of the environment and the wearer's conditions, such as electrical, thermal and magnetic ones [38]. Smart clothing has various functions (e.g., protection, temperature regulation, monitoring, entertainment, expression of personality, etc.) and embodies many features (e.g., efficient, intelligent, computable, etc.), combining cutting-edge technologies in related fields such as electronic information, sensors and materials [39].

The intelligence of clothing is mainly realized in two ways [39]: (1) Ordinary clothing is organically combined with an integrated circuit system to realize the preset functions. For example, sensors, power supplies and other hardware are integrated into a single package through packaging and miniaturization technology and then are attached to clothing. (2) To realize the intelligent functions, flexible wearable technology is used. For example, flexible sensors, thin-film batteries and flexible displays are woven into clothing, or fabrics with functions such as phase change and color change are directly used. In the first way, intelligent modules are separated from fabrics, while the second way emphasizes the integration of smart modules and textiles, with better comfort, flexibility and concealment of electric components, which will be the main trend of smart clothing in the future.

Research on smart clothing originated from the smart medical shirt developed by Georgia Tech Wearable Motherboard (GTWM) [40], a U.S. Navy funded project, in 1996. This shirt was made of optical fibers and special sensors to detect gunshot wounds and monitor physiological signals in a fighting environment. Although research on the wearable system began as early as 1991, the GTWM smart shirt realized the real integration of textile materials and computing technology. As the research continues, the application of smart clothing is no longer limited to the military and is also widely used in aerospace [41], fire protection [42], medicine [40], fitness [43] and other fields.

4.2. General Classification of Smart Clothing

Smart clothing provides a series of personalized services by embedding multiple functional modules on the basis of traditional clothing. According to the function, smart clothing can be divided into various types used for sports and fitness, medical care, safety protection and entertainment, as shown in Table 1.

Smart clothing for sports and fitness is mainly used to track steps, speed, heart rate, calorie consumption and other fitness metrics so as to improve the exercise effect. For example, the Canadian Athos bodysuit [43] integrated several washable EMG sensors in key muscle spots, enabling real-time monitoring of users' heart rate, respiratory rate and muscle mass to avoid injury during exercising. On the basis of tracking users' physiological data, Hexoskin smart vest [3] was equipped with an app compatible with third-party applications (e.g., Strava, Run Keeper, etc.)

Smart clothing for health care is an important trend of the apparel industry. It helps its wearers monitor health status in real time and prevent diseases by accurately collecting and analyzing heart rate, ECG, blood pressure, EMG signals and other health data. The existing achievements include a wearable device with remote monitoring function [44], intelligent bone rehabilitation device [4], etc. LEGSys [45] (a gaits analysis system) developed by BioSensics helps doctors track patients' conditions and adjust treatment plans.

Table 1. General classification of smart clothing.

Types	Main Functions	Target Groups	Representative Examples
For sports and fitness	Record wearers' fitness metrics to improve exercising effect	Sports enthusiasts	Athos bodysuit, Hexoskin vest, etc.
For health care	Monitor users' health data for preventing and curing diseases	The elderly, children, patients, etc.	Remote monitoring equipment, intelligent bone rehabilitation equipment, LEGSys gait analysis system, etc.
For safety protection	Provide safety protection for users to reduce danger	The old, the weak, the sick, the disabled and the practitioners of high-risk occupations	Sensatex baby pajamas, Prop fall-proof coat, ClimaCool racing suit, etc.
For entertainment	Make clothing more interesting and enrich leisure life	The young	Levi's music coat, smart navigation jacket, Teslasuit, etc.

Smart clothing for safety protection is mainly developed for the old, the weak, the sick, the disabled and high-risk occupational practitioners. This type of clothing usually has the functions of alarm, positioning, pollution prevention and high temperature resistance to reduce the wearers' danger in daily life or harsh environments. Sensatex developed special pajamas for babies [46], which will sound an alarm if the baby stops breathing when sleeping. Prop invented an intelligent fall prevention coat [47], which is able to sense the motion of falling and quickly inflate and pop up within 0.1 s to protect the hip, spine, head and other body parts for the elderly. The ClimaCool smart racing suit [48] launched by Adidas is used to recognize identity and store personal medical records so as to provide help for treatment in case of car accidents.

Smart clothing for entertainment focuses on the experience of garments and life, equipped with music playing, video playing, automatic temperature regulation, positioning and navigation and expressing mood and other functions, for example, Levi's music jacket [6], its smart jacket with voice navigation [49] and some wearable equipment based on virtual reality technology. Tesla Studios developed a VR equipment named Teslasuit [50], made of a special intelligent fabric and a large number of sensors to stimulate nerves and muscles through a pulse current to confuse human senses so that wearers can experience the feeling of interacting with virtual game characters.

4.3. Design Principles of Smart Clothing

The difference between intelligent clothing and ordinary clothing is that it emphasizes people's actual needs. In order to meet the requirement, smart clothing has a complicated manufacturing process, high cost and lots of design principles. In addition to style, color and fabric, designers focus on how to combine clothing with electronic information technology. Thus, the design principles can be summarized as intelligent module design and carrier design, in which carrier design includes material design and garments integral design (Figure 3).

4.3.1. Intelligent Modules

Intelligent module design is the core of its difference from traditional clothing design, which involves the frontier technologies in many fields. It can be divided into the following five aspects.

1. Sensor module

Sensor module is the key to realizing intelligent garments. It is used to convert non-electrical signals into electrical signals that are easy to process [51]. Sensing technology can monitor heart rate, blood pressure, sweating rate and other physiological indexes, as well as the changes of environmental information such as temperature, pressure, location, etc. For example, baby pajamas developed by Rest Devices can sense the baby's breathing and temperature through multiple built-in sensors, and the family can view the baby's condition on an app to facilitate nursing [52]. An Italian team Andretta developed a gas sensor and applied it to work clothes, achieving a great effect on gas safety monitoring [53].

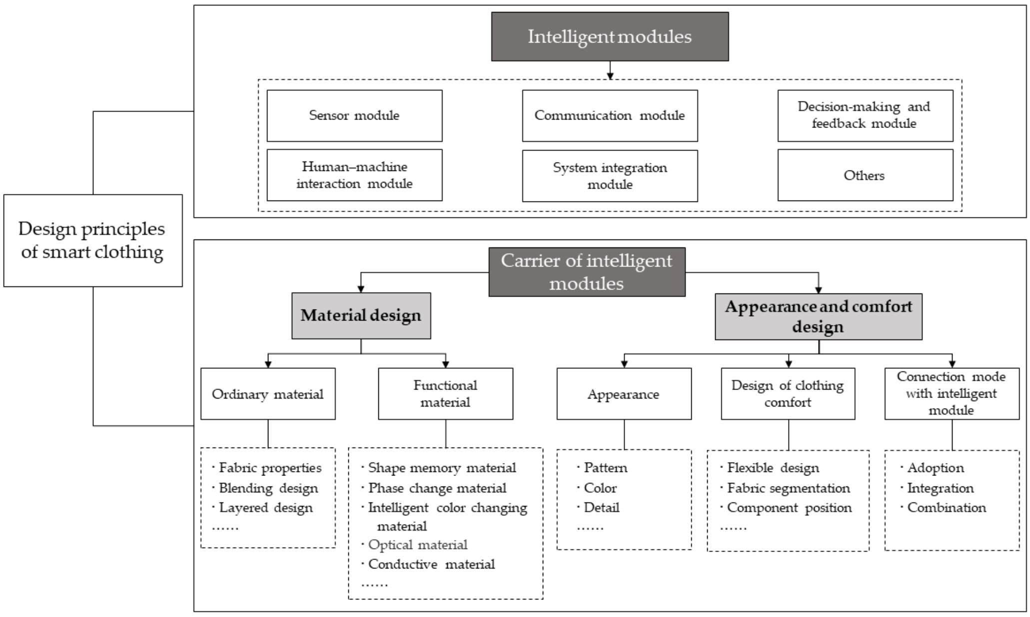

Figure 3. Design principles of smart clothing.

2. Communication module

Communication module transmits the data and information collected by sensors. Communication technology greatly reduces the use of wires and facilitates data transmission. The communication between smart clothing and the data terminal is mainly based on Bluetooth, WiFi, NFC and other technologies. For example, a smart shirt launched by Arrow uses NFC to realize sending electronic business cards and playing music [54]. Japanese researchers designed intelligent clothing that prevents the elderly from getting lost by combining WiFi with GPS, which is convenient for families to know the elderly's location in real time and ensure travel safety for the old [55].

3. Decision-making and feedback module

Decision-making and feedback module is a unit for information collection, processing and transmission. In smart clothing, it is mainly used to extract, transform and analyze the collected physiological or environmental signals, make judgments according to default information and trigger further reactions [56]. Smart clothing can realize communication with people, no matter what the communication form is (e.g., text display, voice feedback, image presentation, etc.). The decision-making and feedback module is essential to process signals and improve reasonable services and guidance.

4. Human–machine interaction module

Human–machine interaction module builds a communication bridge between users and clothing. Human–machine interaction technology, originated from the computer field, is a technology that produces an interactive relationship with the surrounding environment and other organisms through language or behavior based on the needs of users [57]. At present, human–machine interaction technology generally achieves speech recognition, face recognition, gesture analysis and other functions by identifying and analyzing sound, image and other signals.

5. System integration module

System integration module integrates separated modules and function into an interrelated and unified system through computer network technology so as to achieve resource sharing and efficient management [58]. System integration technology includes module integration and function integration. Module integration is the integration of electronic components into a single package, mainly relying on packaging and miniaturization technologies. Function integration refers to the connection and interaction between devices to make function configuration reasonable, which mainly relies on wireless body area network technology, a technology that transmits data to an intelligent terminal by wireless communication technology [59]. For example, users' ECG, pulse, respiration and blood oxygen are monitored at the same time.

4.3.2. Carrier of Intelligent Modules

In addition to the advanced technologies, the intelligence of garments cannot be realized without the design of a carrier. Carrier design can be roughly divided into material design and garment integral design.

1. Material design

The materials used in smart clothing include ordinary fabrics and functional material. The former are used as functional carriers to ensure the basic wearing performance of clothing, whereas the latter is used to improve the functionality of clothing based on the unique properties of fibers.

The adaptability of intelligent components, clothing comfort and usage scenarios should be considered for fabric design. Because the properties (e.g., rigidity and extensibility) of electronic devices such as sensors and processors are quite different from ordinary yarns, the fabric yarns should be selected flexibly according to the position, embedding mode and functional requirements of electronic components. For example, the fabric for emergency rescue should have high strength, high toughness, good permeability and water resistance [42]. In order to improve the comfort of clothing, combining intelligent materials with ordinary yarns through blending or knitting is a common way. For example, phase-change materials are added to underwear fabric to regulate body temperature, and conductive yarn is blended with ordinary cotton yarn to improve the feel and look of the fabric. In addition, fabric layered design is also commonly used in smart clothing, for example, physiological monitoring intelligent clothing applied in fire protection and military. In order to accurately perceive the changes in workers' health condition, the intelligent module should be in close contact with the skin, and thus it is generally placed in the inner layer, which should have the properties of moisture absorption, ventilation, heat transmission and fast drying. The second layer of fabric is used for thermal insulation and minimizing external signal interference. Finally, in order to improve the protection capability further, a third layer can be added to improve the performance in wind resistance, water repellency, temperature resistance and acid resistance [60].

Functional materials have the functions of sensing information, processing information, self-diagnostics, self-repair and so on [61]. The common materials used in intelligent clothing include shape-memory materials, phase-change materials, intelligent color-changing materials, optical materials and conductive materials. Shape-memory material is able to return to its original shape with the right thermal, optical, etc., stimuli [62]. It is mainly applied in clothing for fitness and posture adjustment. Phase-change material enables garments to regulate temperature by sensing ambient temperature [63]. The material is usually applied in pockets, necklines and other positions and is suitable for athletes, sanitation workers, smelting workers, etc. Intelligent color-changing material is divided into photochromic and thermochromic, mainly applied for leisure and recreation, as well as acting as a warning. Optical material is used to sense and transmit data and provide real-time and accurate system information and is widely applied in all kinds of sensors [64]. Conductive material is able to connect various electronic modules to ensure the system works properly [62]. In addition to serving as a connection, conductive fibers are also widely used in flexible sensors. For example, American Circuitex weaved conductive fibers into clothing as sensors to monitor the health status of patients [65]. In addition, with the development of biochemical technology, more new intelligent materials have been developed, such as antibacterial material [66] and anti-impact material [67]. Wang et al. [68] tried to improve the tensile properties and conductivity of fibers applied to smart textiles. Tokyo University developed an invisibility cloak based on visual camouflage, which is made of retro-reflective fibers [64].

2. Appearance and comfort design

The style design of smart clothing requires designers to improve the fashion sense while ensuring garment practicability. Similar to ordinary clothing, the characteristics of targeted consumers should be considered. For example, in terms of color selection, simple and elegant color matching are suitable for the elderly while bright and bold colors are better for the young. In pattern design, children's clothing needs to emphasize fun and novelty. For example, most children prefer vivid and lovely patterns such as cartoon, letter and bionic figures. It is suggested that the concealment of intelligent components be considered in the pattern design. It is necessary to reduce the presence of electronic components through proper arrangement of pattern color, position and shape. In addition, the feedback mode of smart clothing also affects the design. For example, the LED display screen is generally placed on the back, and the light-emitting module is generally built in hems and cuffs. Other detailed designs such as laces and folds can not only play a decorative role but also enhance the concealment of electronic components.

For smart clothing, it is difficult to balance functionality and comfort. For example, the hardness, rigidity and volume of electronic components may cause foreign body feeling or even tingling. At present, flexible electronic technologies (e.g., flexible sensor, skin electronic patch, thin-film battery, flexible screen) tend to be used for improving the comfort of intelligent clothing. For example, Coosemans et al. [69] integrated sensors made of mixed textile materials into baby pajamas. In addition, fabric segmentation design is also a widely used method to improve the comfort of intelligent clothing. Different fabrics should be selected according to the contact area with the skin. For example, fabric close to the neck and the elbow should be soft and elastic [70]. In addition, the position of intelligent components also affects the wearing comfort; thus the areas susceptible to large activity and dirt such as cuffs and necklines should avoid electronics. For example, Liu [71] designed a zipper on the front of the T-shirt to place the locators.

The connection manner between the carrier and the intelligent module is a vital part in smart clothing design. The traditional method makes intelligent components separate from textiles, that is, textiles as a platform for embedded electronics (e.g., pockets) [72]. Pockets are generally located in side seams, hems, hats, etc. As the technology develops, intelligent materials are better integrated with textiles, and thus softer connection modes emerged. For example, the electronic devices are embedded in zippers and buttons [73] or with seamless connection between the intelligent elements and ordinary fabrics by knitting [74], embroidery [75] and coating [76]. Recently, the progress of biochemical technology has inspired designers to directly adopt textile materials with inherent functionalities without considering the connection mode. For example, Solar Active developed yarns that are able to change into orange, blue, red and other colors under ultraviolet irradiation, which can be directly used to make intelligent color-changing clothing [77]. Berzowska et al. [78] designed a shape-memory material in the shape of flowers to decorate the shoulder of a dress, with flowers blooming and closing to the change of temperature.

Various intelligent wearable devices are sprouting up with technological advancements. Wearable devices are the combination of microelectronic devices with daily wearable products [39], such as glasses, watches, backpacks, etc. However, these products have long-term discomfort, insufficient accuracy and many other disadvantages; thus health monitoring through traditional wearable devices is difficult to sustain. In addition, due to the small contact area between wearable devices and the skin, the types and accuracy of collected physiological parameters are relatively limited [79], resulting in the functions being unable to meet the requirements of consumers. As a kind of intelligent wearable device, clothing is in direct contact with about 90% of the skin [80], which has a wider monitoring range and gains more accurate results. Thus, the key to achieving continuous innovation and vitality for smart clothing is to integrate functional components into daily textiles in a softer way, which not only meets the basic needs of consumers for covering and keeping warm but also satisfies the functional needs of physiological monitoring, health protection, leisure and recreation.

5. Current Challenges

Smart clothing, in a broad sense, including all kinds of clothing that plays an auxiliary role for wearers' life and work, is becoming an important direction for the apparel industry because of its extensive functionality. Academia and the industry have always been concerned with its production technologies, which has gradually changed from conceptualization to commercialization. Nowadays, sustainability has gained considerable attention and become the general trend for future fashion. Due to the particularity of materials and development technology, it will be hard to achieve the sustainable development of fashion if smart clothing is mass-produced in the future. This paper concludes the following challenges for the sustainable development of smart clothing.

5.1. Environmental Friendliness

Environmental unfriendliness is an important factor hindering the sustainable development of smart clothing. Because of electronic components, functional fabrics and other materials, smart clothing can easily cause environmental pollution such as radiation, toxic gas emission and carbon emission during manufacturing, utilization, recycling, etc.

5.1.1. Raw Material Processing

The pollution source of the textile industry lies in raw material production, where pesticides, chemical fertilizers and herbicides can cause soil, water and air pollution in natural material planting. The catalysts, flame retardants and other chemicals used in the processing of synthetic materials not only cause environmental pollution but also have adverse effects on human health [81]. MAAP (Monitoring of the Andean Amazon Project) [82] claimed that the destruction of the Amazon rainforest is related to the processing and emission of fibers and fabrics. In addition to the selection of carriers, a large number of electronic materials are included in smart clothing. Moreover, the preparation of electronic devices is more complex, involving laser cutting, electric welding, gluing, electroplating, etc., which results in oil fume, metal vapor, acid-base wastewater and many other pollutants [83,84]. Therefore, compared with ordinary clothing, smart clothing will cause more environmental pollution in the production of raw materials.

5.1.2. Manufacturing

The integration of electronic information technology and material technology improves the complexity of smart clothing manufacturing. The production process of ordinary clothing includes spinning, dyeing, cutting, sewing and finishing [85]. In order to improve the aesthetics and wearability, various chemicals (e.g., dyes, fluorescent agents, whitening agents and moth proofing agents) used in fabric dyeing and finishing can cause serious pollution [86], and dust pollution can occur during fabric cutting and sewing. In addition, the ironing, washing and other finishing links can also emit a huge amount of carbon dioxide and sewage [87]. On this basis, the processing of metals, silica gel, batteries and other materials is added for smart clothing. The combination of these special materials and textiles will lead to fiber powder and tons of metal scrap, which is difficult to collect and degrade, causing damage to the environment.

5.1.3. Disposing and Recycling

Ordinary clothing is mainly composed of cotton, linen, polyester and chemical fibers. Except for natural fibers, the decomposition of other components requires massive water resources and chemicals, producing a large amount of carbon emissions. Due to the addition of electronic and biochemical technologies, smart clothing has a worse impact on the environment when it is disposed of. For example, heavy metals and harmful gases are produced when integrated circuits are disassembled and crushed, resulting in soil pollution, water pollution and air pollution. Wu et al. [88] found that the Cd content of rice growing in the area near an electrical dismantling plant was much higher than that in other areas, which seriously affects the local soil and population health. Due to the current technical limitations, smart clothing still contains quite a lot of electronic devices, which are difficult to degrade, are persistent in pollution and easily cause ecological imbalance.

Because of the poor environmental friendliness of electronic components, the difficulty of material recycling also hinders the sustainable development of smart clothing [89]. Electronic components are highly dispersed in clothing, and the connection between them forms a complex circuit system, which makes it harder to identify and separate these components. Additionally, it is not only difficult to separate the seamlessly connected textiles from intelligent electronics, but it also causes possible damage to the recyclable materials. Therefore, how to improve the recycling technology of electronic components and reduce the waste of polluting materials is also a huge challenge faced by the sustainable development of smart clothing.

5.2. Life Cycle

Product life cycle refers to the period of time that a generation of products go through from entering the market to being eliminated by the market [90], experiencing four stages: formation, growth, saturation and recession [91]. Product life cycle is mainly determined by production technology and consumer demand [18]. Production technology affects the material life, whereas consumer demand determines the market value, which is the key to promoting new products to replace old ones. The life cycle of smart clothing mainly depends on the service life of electronic devices and consumers' preference for the appearance and function of clothing. Generally, consumer demand is affected by the convenience of daily use, sense of fashion and difficulty of maintenance.

5.2.1. Durability

The life cycle of intelligent clothing is shorter than that of ordinary clothing. Regarding material life, the main reason is that electronic devices have poor waterproof, sweatproof performance and are easy to wear and tear, resulting in low durability. In addition, due to limited technology and insufficient energy supply capacity, the functions of smart clothing are hard to sustain. Although there are ways to extend the life cycle of smart clothing such as design disassembly and equipment renewal, the inconvenient maintenance and operability may damage other normal equipment. The short material life accelerates the service life of smart clothing and thus decreases the durability and brings a great burden to the environment.

5.2.2. Convenience

A U.S. study showed that 10% of adults have smart wearable products, but more than 50% said that they do not use them after purchase [92]. The main reason is that they believe these products are only suitable for people with special needs (e.g., firefighters and patients). At present, the immature wearable technology leads to the limited application of smart clothing and forces consumers to abandon and discard them. In fact, most consumers find that complex and advanced functions cannot improve the quality of life but bring much inconvenience. For example, the smart shorts with muscle activation function require users not to wear underwear so that the fabric can contact the skin directly [93]. Some smart socks need wearers to wear secondary components around the ankles [94]. These inconveniences and deficiencies make consumers gradually lose their interest in smart clothing and thus shorten the service life.

5.2.3. Fashion Sense

The fashion sense of smart clothing is also an important factor affecting its life cycle. At present, intelligent clothing is in an excessive pursuit of function and lacks artistic and aesthetic value. A study showed that more than 50% of users expect smart clothing to be more stylish [95]. Poor aesthetics result in products that fail to meet consumers' current aesthetic requirements, let alone long-term fashion trends, which leads to a constant desire to buy new clothing. Outdated design reduces the market acceptance of smart clothing and causes inventory accumulation. Therefore, how to balance the fashion sense and functionalities has become one of the main challenges for the intelligent garment industry to maintain the sustainable development of the environment, economy and society [89].

5.2.4. Maintenance Difficulty

Another important factor that causes the short life cycle of smart clothing is that complicated use and maintenance rules turn the consumers off after purchasing. Intelligent products are relatively difficult to use, and the immature technology requires consumers to take long-term care and management of intelligent clothing. However, the current businesses rarely provide assisting services for use and maintenance. In addition, consumers are rarely willing to take the initiative to spend time and energy on learning how to use products. Therefore, although smart clothing has various functions, the cost of realizing and maintaining these functions often puts consumers off using them. Some even said that they would turn off the intelligent module of clothing to reduce battery loss and maintenance cost [92], which makes smart clothing lose its advantages and uniqueness, resulting in the early termination of its life cycle to a certain extent.

5.3. Market Circulation Efficiency

Sustainable development requires participants in the supply chain to cooperate with each other to ensure the rapid and smooth market circulation so as to realize the virtuous circle of products from producers, through wholesalers, retailers and other media to consumers and, finally, back to producers. However, there are some deficiencies in the market circulation of smart clothing, such as insufficient warehouse and logistics management, low market acceptance, backward marketing mode and lack of recycling technology and mechanism.

5.3.1. Warehouse Logistics Management

Commodity circulation is actually the combination of the transformation of commodity form and ownership and logistics. Each transaction is accompanied by product storage and transportation. Currently, there are many problems in warehousing management, such as low warehousing efficiency [96], unreasonable warehouse distribution [97] and lack of systematic management of information [98]. On this basis, smart clothing has more requirements for warehouse logistics management technology. Due to the special materials, intelligent materials cannot be simply folded and stored like ordinary fabrics, and the product performance needs to be updated in time. However, there is no warehousing and logistics technology specifically for smart clothing, which makes the garments vulnerable to damage during storage and transportation.

5.3.2. Marketing Mode

Nowadays, with the increasing demand of the public for a personalized, instant and interactive shopping experience, KOL (Key Opinion Leader), IP (Intellectual Property), we media and other concepts emerged, indicating the arrival of a new retail era. It is hard for the past marketing model led by businesses to meet the increasingly changeable market segmentation, which can easily lead to excessive inventory and affect the efficient operation of the supply chain. Therefore, based on the Internet, big data and artificial intelligence, a new retail mode committed to the deep integration of online services, offline experience and efficient logistics came into being [98]. As a commodity containing frontier technologies, emphasizing user experience and carrying rich stories, personalized and diversified marketing means are especially needed for smart clothing to promote the products smoothly to the market. From the perspective of economics, as the key to sustainable development, the efficient circulation of the supply chain achieves the rapid transformation of product value. However, the exploration of the marketing mode for intelligent clothing is still in its infancy.

5.3.3. Recycling Mechanism

The circulation of products mainly depends on recycling. However, consumers seldom take the initiative to return garments back to producers or enterprises, and they generally choose to discard waste clothing. There are two main reasons: the promotion of the sustainability concept is not enough, and the secondary recycling mechanism is not perfect.

The recycling for clothing requires consumers to be aware of sustainable consumption. Jang et al. [99] found that consumers' cognition plays a decisive role in their consumption behavior. It is difficult to change the public consumption concept due to long-term habits. Therefore, although many people have realized that randomly discarding clothes may cause damage to the ecological environment, they generally believe that sustainable development has nothing to do with them. This shows that the government, society and other relevant departments should make more of an effort in the release of sustainable policies and the publicity and education of the sustainability concept. In addition, as smart clothing has not been fully popularized, consumers are unconscious of the environmental damages caused by its disposal, which also limits sustainable consumption behavior.

In addition to the weak awareness of the sustainability concept of consumers, the high requirements of recycling technology and the lack of a recycling mechanism also slow down the circulation of smart clothing. The material recycling of smart clothing cannot simply depend on manual decomposition. Osservoort [99] reported that an ordinary electronic device may contain many components. In many cases, the product can only be recycled by breaking it into pieces. Moreover, due to the small size of the smart clothing market, there is a lack of targeted recycling standards and mechanisms. The traditional recycling mechanism for waste clothing from collecting to standardized processing is of high cost and low profit, which makes the operation difficult for recycling organizations [100]. What is more, the existing recycling mode is mainly used for garment collection, without any follow-up processing and service platforms [100,101]. This mode is not suitable for the secondary recycling of smart clothing containing electronic devices. Therefore, relevant departments should formulate a new recycling mode for smart clothing to realize the rapid circulation of the whole industrial chain.

6. Suggestions for Future Development

Although enterprises have responded positively to the sustainable development of intelligent garments, most companies are still in the early stage of exploration. In order to lighten the impact of smart clothing on the ecological environment, society and economy, the design method, production system and marketing mode should be valued. Based on the limitations of smart clothing on sustainability, this section attempts to provide some suggestions for the sustained and sound development of the industry from the three aspects of design, materials and the supply chain (Figure 4).

6.1. Design

With the destruction of the environment, the energy consumption of the apparel industry has attracted widespread attention. As an indispensable part of garment production, design dominates the later manufacturing and selling and has a great impact on the market and environment.

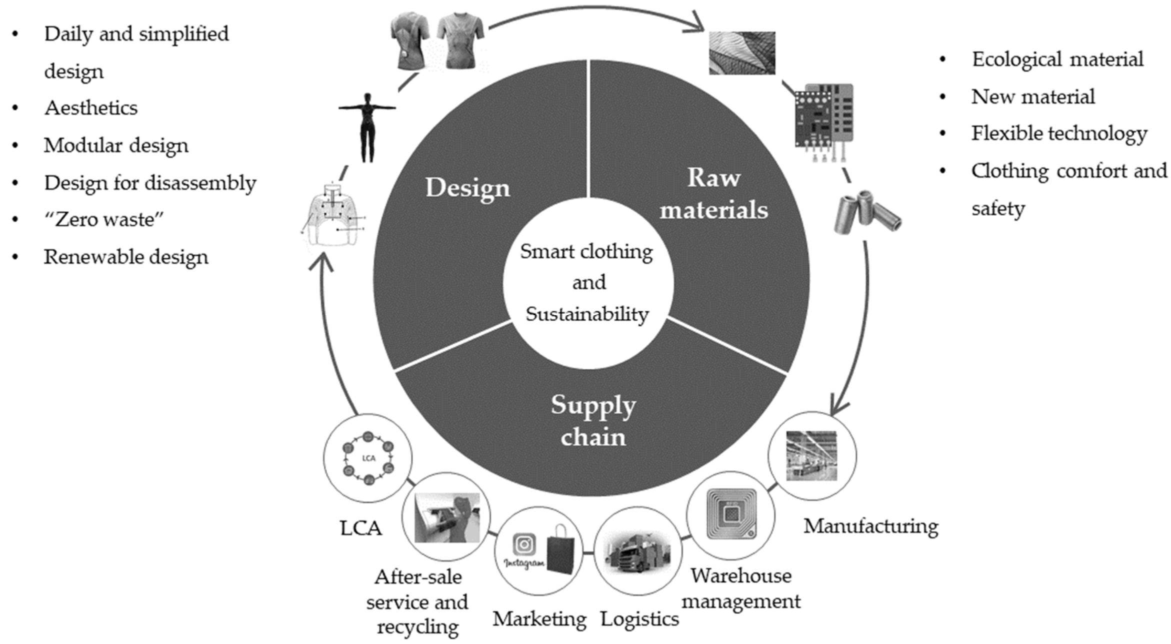

Figure 4. Suggestions for sustainable development of smart clothing.

6.1.1. Generating Daily and Simplified Design

As for low daily utilization and high maintenance difficulty, designers should reduce the use difficulty and complexity of smart clothing so that consumers can enjoy its convenience and comfort in daily life (e.g., walking and rest). In the arrangement of the intelligent devices, designers are responsible for ensuring that users can easily complete the dismantlement, washing, renewal and other work. After all, the higher the usage cost, the lower willingness to buy and use [92]. Designers have the responsibility to help smart clothing enterprises get out of the vicious circle of mass production and random waste.

6.1.2. Enriching Aesthetics

From the perspective of aesthetics, designers should integrate the latest popular elements into garment design to prolong the service life. In addition to traditional design methods, designers can also use scientific and technological means to improve the fashion sense of clothing appearance. For example, wearTRBL developed an online T-shirt using e-ink technology. Wearers can upload and customize T-shirt patterns through an app [102]. Based on reactive dyes, a British company launched a series of bags that can change color according to ambient wind, temperature and light [103]. In addition, in order to achieve consumers' emotional dependence, designers should pay more attention to consumers' real inner needs, such as the psychological difference and novelty of the young and the inferiority complex of patients. What is more, designers can also invite consumers to participate in the design of smart clothing, as the design integrating consumers' own ideas and creativity will effectively improve the frequency and duration of use.

6.1.3. Broadening Design Ideas

The design of smart clothing is not a simple combination of style, color and fabric. Designers could use a big-picture perspective to broaden design ideas from the relationship between the clothing life cycle and sustainable development.

1. Modular design

Intelligent clothing is a kind of special functional clothing, and thus modular design can be helpful. In this way, clothing is divided into multiple independent parts, which can be combined freely according to the needs of users to realize the function of one object with multipurpose [102]. Modular design has many advantages. On the one hand, the independent module facilitates the later repair, maintenance and disassembly. On the other hand, consumers can easily use the intelligent product based on some basic rules without knowing its internal structure, which optimizes the user experience. In addition, modular design helps to reduce the difficulty of recycling electronic devices and secondary utilization, as well as prolongs the life cycle of integrated clothing.

2. Design for disassembly

Design for disassembly refers to the connection of the garment parts through buttons, zippers, pockets, etc., so that each part can be disassembled and assembled freely [104]. Faced with an increasingly urgent demand for environmental protection, this approach offers a more flexible, interesting and fashionable choice than those that limit consumers to buying new products and makes it easier to meet consumers' actual needs for modeling. Nowadays, intelligent clothing still relies on integrated circuits. The detachable electronics increase the washability and wearability of clothing. In addition, the disassembled parts can be used as independent products to achieve other purposes and prolong the life cycle of materials.

Note that the future direction of intelligent clothing is flexibility and integration. Integrated circuit is only a temporary phase in the development of flexible wearable technology. Therefore, modular design and design for disassembly are just temporary ways to improve the sustainability of smart clothing.

6.1.4. Developing Eco-Friendly Design Techniques

Sustainable design requires designers to focus on environmental protection and take into account the impact of products on the environment, economy and society based on the functionality of clothing.

1. "Zero waste"

The idea of "zero waste" requires designers to fully consider the actual application, endeavor to eliminate the waste in garment production and reduce the consumption of natural resources [105]. As a kind of special clothing, design for intelligent clothing can also learn from the principle of "zero waste" of ordinary clothing in carrier design. For example, virtual design, simulated cutting and other new technologies can be used to realize the maximum utilization of materials and reduce waste. Since most electronic devices are made of environmentally unfriendly materials, the concept of simplifying materials and circuits should also be followed in the design of intelligent modules.

2. Renewable design

Renewable design refers to reusing or recreating waste resources so as to reduce the damage to the ecological environment [106]. In the field of apparel, recreating design refers to the repair and reuse of used materials and endowing them with new aesthetics and functions [105]. For example, damaged, defective or useless components are replaced by new materials or materials with other functions to realize the renovation or recovery of functions. In addition, through the extraction and retention of waste materials, "intelligence" can be transferred to ordinary clothing to enhance its value. Additionally, new garments can be made by using some entertainment functions of abandoned smart clothing, such as glowing, color changing and music playing.

6.2. Raw Materials

Raw materials are the fundamental difference between smart clothing and ordinary garments. There are two aspects to realize the sustainability of intelligent clothing from materials: textile materials and intelligent components.

6.2.1. Textile Materials

The concept of environmental protection can be easily addressed in the practice of fashion design. Therefore, recently, most clothing brands have responded to the call for sustainable development by using ecological fabrics [107]. Ecological materials cause little damage to the environment during their production, and thus they should be vigorously promoted to replace the traditional materials with high pollution. In addition, McQuillan [108] believed that organic material is also a desirable choice to solve the problems of resource waste and environmental pollution. These green, ecological and recyclable materials are conducive to the follow-up work and realize the value regeneration of smart clothing.

Just replacing ordinary textiles with ecological raw materials does not mean that it is totally beneficial to the sustainable development of smart clothing. For example, a lot of chemicals have to be used for the planting of cotton and ramie. Developers should balance the pros and cons and strive to find new materials and energy that are harmless to people and the environment. New and healthy materials provide more choices for fabric selection and play a vital role in improving the sustainability of intelligent clothing. Moreover, relevant enterprises should devote themselves to studying innovative material technology to solve problems from the source. For example, the existing self-healing nanomaterial [109] not only increases the recycling rate but also reduces the difficulty of equipment renewal for consumers and after-sale workers. What is more, materials that can decompose themselves under the stimulation of high temperature, microwaves, magnetism, etc., [110] can also be applied. Printing the circuit and sensing materials on the textile surface through this stimulus-dissolving adhesive can effectively reduce the difficulty of recovery and damage to other materials during disassembly. A waterproof and breathable fabric developed by Luo et al. [111] was found to be able to protect textiles from oxidation, which effectively improves product life cycle.

6.2.2. Electronic Components

For smart clothing, in addition to the chemical fiber pollution caused by fabrics, electronic devices (e.g., sensors, batteries and LCD screens) tend to cause more pollution and are harder to recycle. What is more, traditional electronic components are mostly bulky, rigid and not machine-washable, which greatly reduces the life cycle of intelligent clothing. Whereas flexible technology renders electronic components with flexible, foldable, extendable and other properties [70], the metal content of materials is lowered to improve the renewability and degradability of electronics, and the radiation can be reduced by some finishing processes such as coating [112,113], which is assumed to effectively improve the wear resistance and service life of the garments. Gao et al. [114] developed a flexible nanocomposite with high-conductivity and -sensing properties through ultrasound and hydrophobic interaction. In addition, some flexible ultra-thin materials also help to save materials and improve resource utilization.

Sustainability emphasizes the principle of “integration of clothes and people”, but the electronic components are not completely harmless to people due to the immature technology. Therefore, more attention should be paid to the wearing comfort and safety of smart clothing. For example, in order to reduce the discomfort caused by the close contact between intelligent components and the skin, Li et al. [115] proposed an intelligent garment design method combining knitting technology and the fashion design concept. In this method, different stitches were used for different fabrics to maintain proper confining pressure and conductivity, which improves the aesthetics and practicability of smart clothing. The flexibility of sensors can also be improved so that the electronics can directly contact the skin [116]. The particularity and functional diversity of intelligent materials are prone to cause potential safety hazards to consumers [117]. Therefore, the intelligent apparel industry needs to strengthen the cooperation with talents in multiple fields, not only to avoid the physical damage caused by intelligent modules but also to focus on the security of the information network to protect personal privacy.

6.3. Supply Chain

In Sustainable Fashion and Textiles, Kate Fletcher argued that the existing supply chain modes of globalization, low cost and high output explain that the concept of sustainability is affecting the development of the fashion industry [118]. The sustainability of smart clothing cannot simply rely on fashion designers and raw materials; the supply chain should also be emphasized. A sustainable supply chain attaches importance to the closed-loop mode that starts from the production of raw materials and ends with waste recycling.

6.3.1. Manufacturing

Under the background of sustainable development, the manufacturing industry is also facing pressure from global escalation. In the information and digitization era, intelligent manufacturing has become an important means to realize the upgrading and transformation of the apparel industry and the core technology for the future manufacturing industry. Thus, in order to improve production efficiency, it is necessary to optimize the technological process and manufacturing mode of smart clothing. As the customized product has various kinds and rapid changes in demand, intelligent clothing is well suited for a flexible production mode. Relying on modern information technology, this mode is able to organize production according to the personalized demands of consumers and respond quickly to market demand to avoid losses, minimize inventory and maximize benefits [119]. In addition, multi-variety, small batch and fast response are the characteristics of the current mainstream production mode. It is no longer limited to a single assembly line, realizing optimal production through rational allocation of labor and resources. For example, the fast-fashion brand Zara carried out localized production and made full use of local small-scale production in its global supply chain to realize sustainable development [118]. Smart clothing enterprises can learn from Zara to reduce the regional production scale and adopt localized production to save logistics time, improve operation efficiency and maximize benefits. In addition, the Internet Plus platform is also calling for stronger flexibility in manufacturing; thus companies should get better guidance for production by analyzing consumer preferences and sales data based on data mining technology. In addition, intelligent manufacturing also helps to manage carbon footprint, water footprint, environmental pollution and resource waste. Moreover, at the end of the production process, it is necessary to strengthen the environmental protection test. In fact, there is no detailed description of the harmful substances that clothing contains or perfect test standards and methods, leading to enterprises being unable to declare the safety of products [120]. Therefore, relevant departments should take the responsibility to study and formulate standards for the detection of harmful substances in smart clothing as soon as possible to promote the lasting and sustainable development of enterprises.

6.3.2. Warehouse Management

The apparel industry features a short cycle and fast delivery. The seasonality and diversity of garments determine that enterprises need an efficient warehouse management system. The traditional clothing warehouse management mode has a complicated process and large consumption of labor and materials, which affects sales efficiency and consumer satisfaction. In addition, current intelligent clothing is still based on an integrated system containing a large number of electronic components. The particularity makes it almost impossible to be simply folded and stored like ordinary clothing. In order to effectively manage and maintain smart clothing, the management system should do the following [121]: (1) identify the smart clothing separately and synchronize all the data about clothing so as to facilitate rapid search and improve sales efficiency; (2) provide necessary energy support for long-term intelligent clothing storage; and (3) conduct regular performance diagnosis to avoid failures and accidents due to external factors.

Nowadays, some new warehouse management technologies have been developed. For example, RFID (Radio Frequency Identification), a wireless identification and acquisition technology, replaces the traditional manual counting, work ticket and barcode recording modes in the workshop, breaking the framework of the traditional production management mode. It promotes the effective allocation of resources by flexible control and strengthening customer relations [122]. RFID can also be combined with NB-IoT (Narrow-Band Internet of Things), a network communication technology of low power consumption and wide coverage, capable of reducing the operation time of warehouse management [123]. Some garment companies also combine the ERP (Enterprise Resource Planning) system with e-commerce to strengthen the communication between customers and suppliers, thus simplifying the transaction process [124]. More efforts should be made to explore new technologies for intelligent clothing management on the basis of using mentioned traditional systems. For example, Aaron et al. [121] designed an intelligent clothes hanger system, Hbar, by innovating the existing management system to automatically detect intelligent clothing and provide power for intelligent clothing.

6.3.3. Logistics

Green logistics plays a vital role in realizing a sustainable apparel supply chain [14]. It means that products are environmentally friendly during transportation, with particular emphasis on reducing carbon emissions. Due to multiple types and small production, smart clothing has a wide distribution. Thus, relevant companies should select reasonable regional distribution centers for smart clothing through macro control and establish an information-based distribution system. In addition, full consideration should be given to the distribution of resources and transportation networks in the sale area to avoid circuitous transportation of goods and reduce fuel consumption and demand for the road area.

In addition to macro control, advanced logistics technologies should be adopted to reduce carbon emissions during transportation. For example, the logistics information system based on GPS or GIS realizes the sharing of logistics resources and reduces the amount of ineffective work through big data so as to reduce energy consumption and pollutant emission. In addition, researchers are also exploring how to realize green logistics from other aspects. For example, Garcia et al. [125] proposed a method to realize sustainable logistics from packaging. Currently, smart clothing has high requirements for transportation packaging due to technical restriction. Reasonable packaging materials and packaging combinations also affect the carbon emission of the overall supply chain. Therefore, packaging is also an important direction to realize the green logistics of intelligent clothing in the future. Organic crops, paper and wood-based materials primarily used for food can also be considered for apparel products [126].

6.3.4. Marketing

Although consumers have a certain consciousness of ecology and environmental protection, the inclusion of sustainable means may further increase the price of products. Therefore, not many consumers are actually willing to buy sustainable clothing, which causes fashion enterprises to think about the marketing of sustainable products.

The marketing for sustainable intelligent clothing can be considered from the aspects of publicity, packaging and the marketing environment. Enterprises should continue to strengthen the promotion of the sustainable development concept, give full play to the advantages of the New Media Era and guide consumers to carry out sustainable consumption. Soft ways to disseminate information such as social media should be adopted to improve the acceptance of the concept of sustainability and encourage consumers to actively participate in related activities. Moreover, environment-friendly, recyclable and degradable materials should also be used to make product packaging as a way of publicity for smart clothing. It is also advisable to add sustainable logo certification on the cover to build a green and sustainable brand image. In addition, KOL (Key Opinion Leader) marketing, precision marketing, community marketing and other online marketing methods should be actively adopted [127]. New trends are more attractive to Internet users who are also the main force of smart clothing consumption in the future. Therefore, enterprises should make full use of big data and the network to truly understand consumer demands while promoting merchandise, trying to develop a new marketing mode and promoting the sales of sustainable intelligent products. For example, luxury brands such as Burberry [128] and Louis Vuitton [129] have taken the lead in using big data to tap into their clients' personalized needs. Similarly, smart clothing has a relatively small customer base, and thus, to some extent, they can learn from the practice of luxury brands. In addition, in today's world of social networking, Facebook, Weibo and other self-media shall be considered as important channels to collect greatly diversified consumer data and provide products and services with precision.

6.3.5. After-Sale Service and Recycling

Due to the unique performance of its raw materials, smart clothing causes more environmental pollution in its use and disposal. Therefore, it is necessary to take some sustainable measures for its after-sale service and recycling. For example, enterprises can track the after-sale carbon emissions through service tracking technology and monitor pollution data during the use of products by GPS positioning, environmental monitoring sensors and other real-time monitoring devices. MIT SENSEable laboratory has launched the "CPH Wheel Project" [127], where they developed a bicycle with some data monitoring sensors on the wheels, capable of sending information about gas emission and road use to a mobile terminal. Meanwhile, enterprises can collect relevant data backstage to understand the situation of actual use and environmental impact. In addition, enterprises should strengthen the after-sale service quality and prolong the service life cycle. For example, usage instructions, software updates, component maintenance and other services can be provided to reduce the use difficulty and cost so as to encourage consumers to increase their daily use frequency and enhance the value of smart clothing.

Compared with ordinary clothing, it is harder to deal with waste smart clothing. However, in the face of the increasingly serious problem of garment waste and pollution, the recycling and utilization of intelligent clothing have become an important breakthrough to realize its sustainability. Apart from encouraging professional recycling companies, charities and social service departments to join the recycling of smart clothing, recycling services should also be provided by other relevant parties in the chain. After recycling, the waste garment should be decomposed and classified, and the rare components and metal materials in electronic devices should be utilized as much as possible. In order to ensure that smart clothing can be quickly identified in a large number of waste textiles, some labels should be considered. The electronic material information is stored through digital ID such as the QR (Quick Response) code [130], and the information such as material category and degrees of depreciation is transmitted to the recycling institutions to facilitate the destruction of waste materials or further processing of secondary creation.

6.3.6. Life Cycle Assessment

The discussion on ecological and low-carbon strategies of smart clothing from the perspective of the life cycle is helpful to more comprehensively monitor and evaluate the impact of smart clothing. The Life Cycle Assessment (LCA) method, proposed by the Society of Environmental Science and Chemistry in 1993, refers to a set of systematic methods for collecting and measuring the environmental impact and the input and output of material and energy in the whole life cycle [131]. The impact on the environment is mainly evaluated by calculating the carbon emissions generated in the product life cycle at present.

The life cycle of smart clothing consists of raw material acquisition, production, logistics, sales, use and recycling, and every phase involves carbon emission and environmental pollution. The field of smart clothing has hardly implemented LCA in practice, but some research has been carried out, such as carbon footprint and carbon label certification. For example, the carbon emission during the production of jeans was studied, and different carbon footprint models in spinning, weaving, garment and washing stages were established so as to serve the green production and design of jeans [132]. Aiming to explore the impact of nanotechnology on the environment in the mass production of textiles, Walser et al. [133] prospectively evaluated the life cycle of nanosilver T-shirts. Considering the impact of electronic inkjet on the future development of smart clothing, Kanth et al. [134] conducted a study on the LCA of this technology in antenna printing. Since 2018, life cycle assessment has been determined as the only criterion for the sustainable evaluation of leather products according to EU environmental policies [135]. The LCA of smart clothing should focus on energy supply, material integration, actual use and waste disposal. Compared with ordinary textiles, the carbon emission of smart clothing mainly focuses on the production, manufacturing and disposal of electronic components. Enterprises need to use advanced information-tracking technology to calculate the carbon emission of each phase involved in the life cycle so as to reduce the environmental pollution caused by smart clothing in a digital and scientific way.

7. Conclusions

As a combination of information, computer and micro-electronic technologies, smart clothing enriches consumers' daily life. Although it is still in its early stage of development, the progress of wearable technology will make it popular in the future. However, the service life of fabrics and electronic devices is relatively short, and the growing demand exacerbates the production and abandonment of intelligent clothing. The concept of sustainable fashion relies on the ecological management mode, complying with the development requirements of the times. Combining intelligent technology with the concept of sustainable development improves the market acceptance of intelligent clothing, accelerates its mass production and promotes the lasting development of the industry. Nowadays, there has been extensive research on sustainable fashion, but research on smart clothing is limited. Therefore, taking smart clothing as the object, this review explores its development status and existing limitations of intelligent clothing under the background of sustainable development and puts forward corresponding suggestions.

From a macro perspective, the main factors restricting the healthy development of the fashion industry are design, commercial value and social environment. Focusing on the field of smart clothing, through the analysis of its characteristics and development status, this paper puts forward a series of strategies for realizing sustainable development of smart clothing in the future. From the basic characteristics, the design principles are concluded into two aspects: intelligent module design and carrier design. This paper focuses on the connection modes between intelligent modules and textiles and finds three principal methods: adoption, integration and combination. Next, it is found that the sustainable development of smart clothing is mainly restricted by poor environmental friendliness, short life cycle and low market circulation efficiency. Finally, the suggestions based on design methods, materials and supply chain for the sustainable development of smart clothing are presented. Designers are encouraged to integrate more popular elements into smart clothing, broaden design ideas and pay more attention to integrating the idea of sustainability into the design. In terms of material selection, enterprises are responsible for developing and using ecological materials and emphasizing the development of flexible wearable technology to improve the comfort and safety of smart clothing. Finally, from the perspective of the supply chain, it is suggested to adopt intelligent manufacturing technology so as to reduce pollution and resource waste caused by production, storage and logistics, give full play to the advantages of the New Media Era and use effective marketing methods to guide consumers to sustainable consumption. In addition, enterprises should concentrate more on LCA and use the latest data-tracking technology to calculate the carbon emission of smart clothing in the whole supply chain to reduce the environmental pollution of smart clothing through digital and scientific methods.

Sustainable development is the future global direction. By combining smart clothing with this trend, this paper provides some references for future policy making and technology development in the field of smart clothing. The supply chain design based on the concept of sustainable development accelerates the commercialization of this field and provides a strategic direction for the lasting survival of smart clothing and other intelligent products.

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