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Review of Carbon Emission and Carbon Neutrality in the Life Cycle of Silk Products

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Abstract
Silk is a distinctive and significant category of natural structural protein fiber. With a remarkable structure and versatility, silk has emerged as a topic of scientific study perennially because of its chemical, physical and biological properties. Meanwhile, in order to have an omnifaceted understanding of silk, the environmental performance of silk production is also worthy of attention. With the concern of global warming, efforts are increasingly focused on understanding and addressing carbon emission in the life cycle of silk products. However, the majority of current studies give priority to the carbon emission of either just one or a few stages of silk products' life cycle, or to a specific type of silk product. On the basis of a review of literature on the life cycle assessment of silk products, this study presents a full-scale review of the quantification of the carbon emission and carbon neutrality of cocoon acquisition, industrial production of silk products, distribution, consumption, and recycling. The analysis revealed that the carbon sequestration by photosynthesis at the stage of cocoon acquisition could not be ignored. It is of importance to establish complete and unified system boundaries when quantifying carbon emissions in the industrial production of silk products. Reasonable models of washing times and washing modes are needed to assess carbon emissions in the domestic laundry of silk products. At the end of life phase of silk products, the positive impact on carbon emission in the phase of silk recycling is noteworthy. This study will help interested scholars, manufacturers and consumers to gain an in-depth understanding of the carbon emissions and carbon neutrality of silk products, and it is also of great value for exploring new production processes for reducing carbon emissions of silk products.

Keywords
carbon footprint, carbon neutrality, silk products, life cycle.

1. Introduction

Silk, as a natural protein fiber, has overwhelmingly different mechanical properties from other natural textiles. It is non-synthetic, renewable, and biodegradable. Great value is given to its characteristics of good trim, lightness, gloss, strength, and softness. It also has a neutral pH, high absorption capacity, elasticity, and anti-static properties. Silk fabric is very comfortable and is used in clothing such as blouses, dresses, shirts, shawls, ties and gloves, as well as for decorating curtains, cushions and upholstery. Silk is also used in the electronic, aeronautical, and medical industries [1]. In 2020, the world leaders in silk production are China at 53369t/y, India at 33770t/y, Uzbekistan at 2037t/y, Vietnam at 969 t/y, Thailand at 520t/y, and Brazil at 377t/y [2].

With the intensification of global warming, there is growing concern to understand and address greenhouse gas emissions during the life cycle of textiles used in people' s daily life, including various clothing, shoes, hats, bedding, etc. Information on greenhouse gas emission in products' life cycle can be displayed to consumers by means of carbon footprint (CF) labels. Based on ISO 14067, the carbon footprint of a product is the sum of greenhouse gas emissions and removal in a product system, expressed as CO_2 equivalent and based on a life cycle assessment [3]. It is the term used to evaluate the total amount of greenhouse gas emissions that are directly and indirectly caused by an activity or are accumulated over the life stages of a product [4,5]. Carbon footprint is one of the important concepts in the research field of "footprint". It emerged in the UK and developed rapidly under the promotion of academia, non-governmental organizations, and the news media. By now, researchers, as well as some textile and apparel companies have calculated the carbon footprint of several textile and apparel products, such as polyester fabric [6], cotton fabric [7,8], hemp [9], flax [10], wool [11,12], nylon textile [13], etc. A couple of studies on the carbon footprint in the manufacture of silk products could also be found in the existing literature. Barcelos et al. [14] undertook a life cycle assessment of the core processes of mulberry and silk cocoon production, and obtained carbon footprint results for the production process. Astudillo et al. [15] conducted a life cycle assessment (LCA) of raw silk, where the authors assessed mulberry production, silkworm rearing, cocoon drying, and cocoon reeling, and obtained carbon footprint results for the life cycle. Ren et al. [16] studied the environmental impact of 100 kg of silk textiles and analysed the global warming potential. Jiang et al. [17] undertook the carbon footprint assessment of gambiered canton silk and the results demonstrated that the total carbon footprint was determined as 1.88 kg CO_2e per one meter of fabric. Faragò et al. [18] calculated the environmental impact of yarn-dyed silk fabrics, printed silk fabrics and dyed silk fabrics, and analysed the results of global warming potential (GWP). Yin et al. [19] presented an environment-friendly production route to produce mulberry spun silk yarns. Giacomin et al. [20] focused on economical and environmental issues of silk production in Brazil and presented some uses of silk residues (by-products) in the fashion and decoration sectors.

Nonetheless, studies analysing carbon emissions throughout the whole life cycle of silk products are scarce. The whole life cycle of silk can be broadly divided into the following stages [1]: the cultivation of mulberry trees, sericulture, reeling of raw silk, processing of silk yarns into fabrics, dyeing and finishing, manufacturing of products, retailing, washing, drying, ironing, reuse and recycling. From the former researches it can be found that the current studies focus on the carbon emission of either just one or a few stages of silk products' life cycle or on a specific type of silk product. Few studies have analysed carbon emissions and carbon neutralisation throughout the whole life cycle of silk products. In this study, we aim to address this gap by clarifying the carbon emissions and carbon neutralisation in the whole life cycle of silk products according to carbon footprint methodologies. Field research and relevant literature were reviewed in order to obtain high quality data to get a clearer result. This study will help interested scholars, manufacturers and consumers to gain an in-depth understanding of the carbon footprint of silk products, and it helps to explore new processes to reduce carbon emissions of the whole life cycle of silk products.

2. Carbon footprint of cocoon acquisition

The stage of cocoon acquisition is mainly composed of mulberry production and silkworm rearing. The main physical inputs in the rearing process are mulberry leaves. As a fast-growing tree, the mulberry starts to produce commercial quantities of leaves for the cultivation of silkworm within one year of planting [21]. The mulberry leaf is an important material basis for cocoon acquisition. The production process of mulberry trees needs the input of electricity, fertilisers and pesticides, which generates carbon emissions during these inputs into the production [22]. In the process of silkworm rearing, the hot spots are the transport of mulberry leaves to feed silkworms and the electricity consumption for lighting and heating. Additionally, rearing beds should be strongly disinfected to avoid the spread of disease, and lime is usually used to disinfect silkworm houses, causing carbon emission.

The carbon sequestration effect of mulberry is rarely mentioned in former studies about the carbon footprint of silk products. Garcia Jr et al. [23, 24] illustrated that mulberry trees had a high capacity for carbon mitigation. Srikantaswamy and Bindroo [25] argued that the production of mulberry biomass had attractive qualities to sequester carbon because of its rapid growth and wide adaptability. Carbon footprint mitigation is done by photosynthesis that sequesters CO_2 from the atmosphere, reducing the global warming effect. A study conducted in 2020 demonstrated that the net carbon emission of mulberry production was negative, indicating that the carbon emission was less than the photosynthesis carbon sink and that mulberry production had a positive externality to the ecological environment [22]. From this perspective, mulberry planting can contribute carbon neutrality to the production of silk.

According to research results that are listed in Table 1, approximately 81.65 tons of CO_2 are fixed in one hectare of mulberry per year, of which 64.80 ton are fixed in mulberry leaves, branches and other above ground parts. Based on the theory of this study, we can deduce that mulberry fields in Baoji, China produced 27.30 tons of mulberry leaves per hectare in a year, and the CO_2 mitigation level was 40.05 tons/ha/yr [26]. Mulberry fields in Fenggang, Guizhou, China produced 31.67 tons of mulberry leaves per hectare in a year, and the CO_2 mitigation level was 52.26 tons/ha/yr [27]. Moreover, the above ground level biomass production of mulberry fields in Jiaxing, Zhejiang, China was 69.36 tons/ha/yr, which fixed 114.44 tons of CO_2 in one hectare of mulberry per year [28].

China is the world' s largest cocoon and silk producer. The production of cocoon and silk in China accounts for more than 80% of global production and the production of raw silk in China for 58% of world manufacture [2, 29], The total gross area of mulberry fields was 788720 hectares in 2017 [30]. It can be estimated that Chinese total mulberry fields can fix 64.40 million tons of CO_2 annually, as shown in Fig. 1. In 2017, the cocoon output of China was 0.64 million ton, containing 0.11 million tons of silk, with a 17% average content of silk in cocoons [24]. Silvia et al. [15] pointed out that 0.45 kg of CO_2 was released per kilogram of cocoon produced during mulberry cultivation and cocoon production. Based on this result, the Chinese sericulture production emitted 0.0495 million ton of CO_2 in 2017. In 2020, Chinese silkworm cocoon production was 0.687 million tons, while the gross area of Chinese mulberry fields increased to 807847 hectares. In this context, the CO_2 absorbed at the mulberry planting stage is much larger than that emitted at the cocoon acquisition stage. The reliable silkworm cocoon output in the whole world in 2020 was 663083 tons; therefore, the global mulberry field has great carbon sequestration achievement [31].

3. Carbon footprint of industrial production

The industrial production of silk products is an activity starting from cocoon handling and passing through spinning, weaving, dyeing, finishing, cutting, sewing and packaging [32]. These production processes consume electricity, steam, fossil fuels, fresh water, chemicals, and packaging materials, and generate carbon emissions, wastewater and other wastes, as shown in Fig. 2.

After the cocoons have been harvested during the rearing activities, cocoon pre-treatment stages (known as silk reeling)

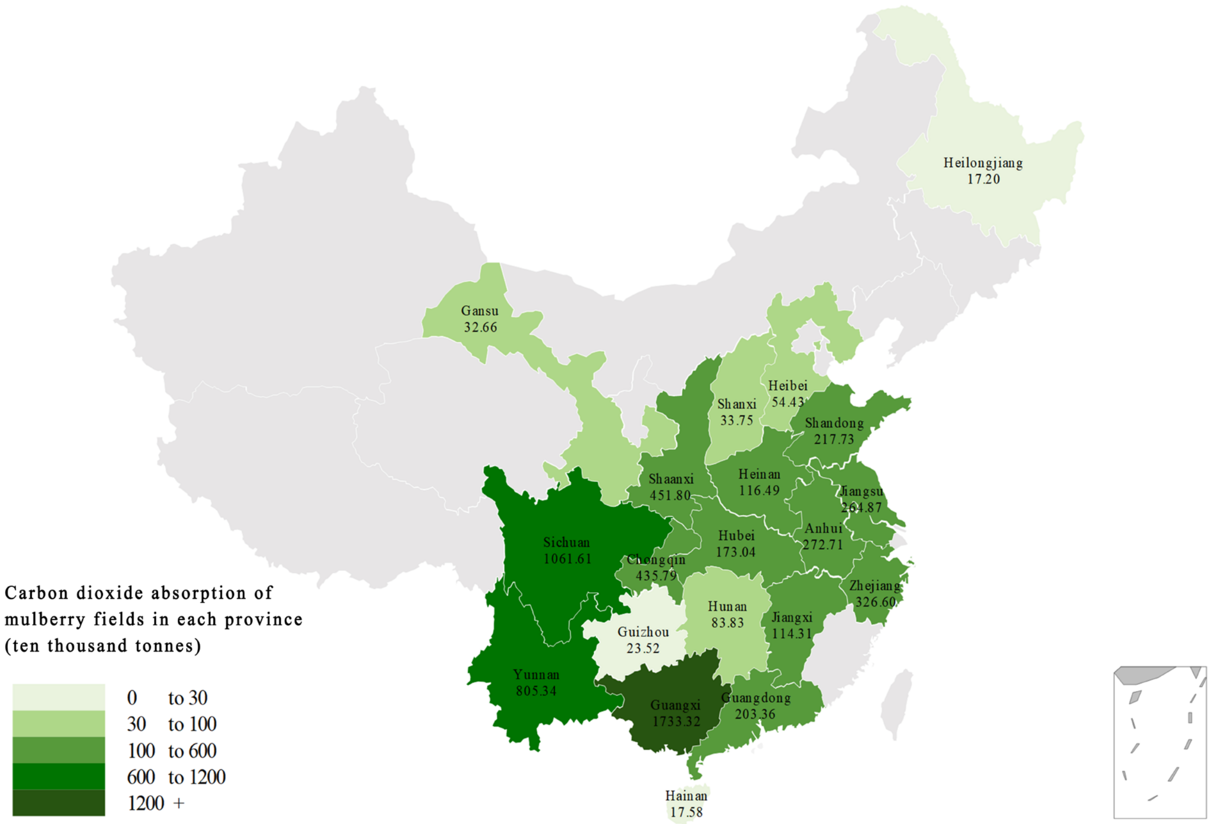

Fig. 1. Carbon dioxide absorption of mulberry fields of each province in China in 2017

Habitat	Above ground level biomass production (tonne/ha/yr)	Above ground level carbon stock (tonne/ha/yr)	Above ground CO_2 mitigation level (tonne/ha/yr)	Total biomass (tonne/ha/yr)	Total carbon stock (tonne/ha/yr)	Total CO_2e mitigation level (tonne/ha/yr)
Brazil [23]	40.00	18.00	64.80	50.40	22.68	81.65

Table 1. Biomass and carbon production in Brazilian mulberry fields

are carried out, such as cocoon sorting, riddling, drying, cooking, reeling, rewinding and twisting [33].

Carbon emission in industrial production mainly originates from electricity and heat. Several production processes such as spinning, knitting and weaving are carried out by machine, which involves a substantial amount of electricity and generates carbon emission and solid wastes [34]. Many processes require high temperature conditions, especially drying, boiling, printing, dyeing and finishing. In countries with backward production conditions, large amounts of fuel such as coal, gas and even wood are used to produce heat, releasing large amounts of carbon during combustion. Meanwhile, in existing silk-producing countries, a large proportion of electric power comes from thermal power, which indicates a large amount of carbon emission. These sources of carbon emission are readily conceivable, but in addition to the carbon emission caused by electricity and heat, the process of silk production also uses many auxiliary accessories, such as chemicals, buttons, zips, tags, inner liner, etc, which cause indirect carbon emissions during their production process, rather than afterwards.

Some studies have focused on carbon emission assessment of the industrial production of silk products. Ren et al.[16] calculated the global warming potential for producing 100 kg of silk products and concluded that carbon emission during the life cycle from cocoon to fabric was 18.563 kg. A UK organization, Waste & Resources Action Program (WRAP), conducted an analysis of the carbon footprint from fiber production to the end of life for silk products [35], illustrating that the carbon footprint was 21820 kg of CO_2 equivalent per ton of silk produced from the production of fiber to the garment. Faragò et al. [18] calculated the GWP of 100 kg of yarn-dyed silk fabrics, printed silk fabrics and dyed silk fabrics open-width, the result of which is 1820.97 kg CO_2eq, 1912.59 kg CO_2eq and 1846.98 kg CO_2eq, respectively.

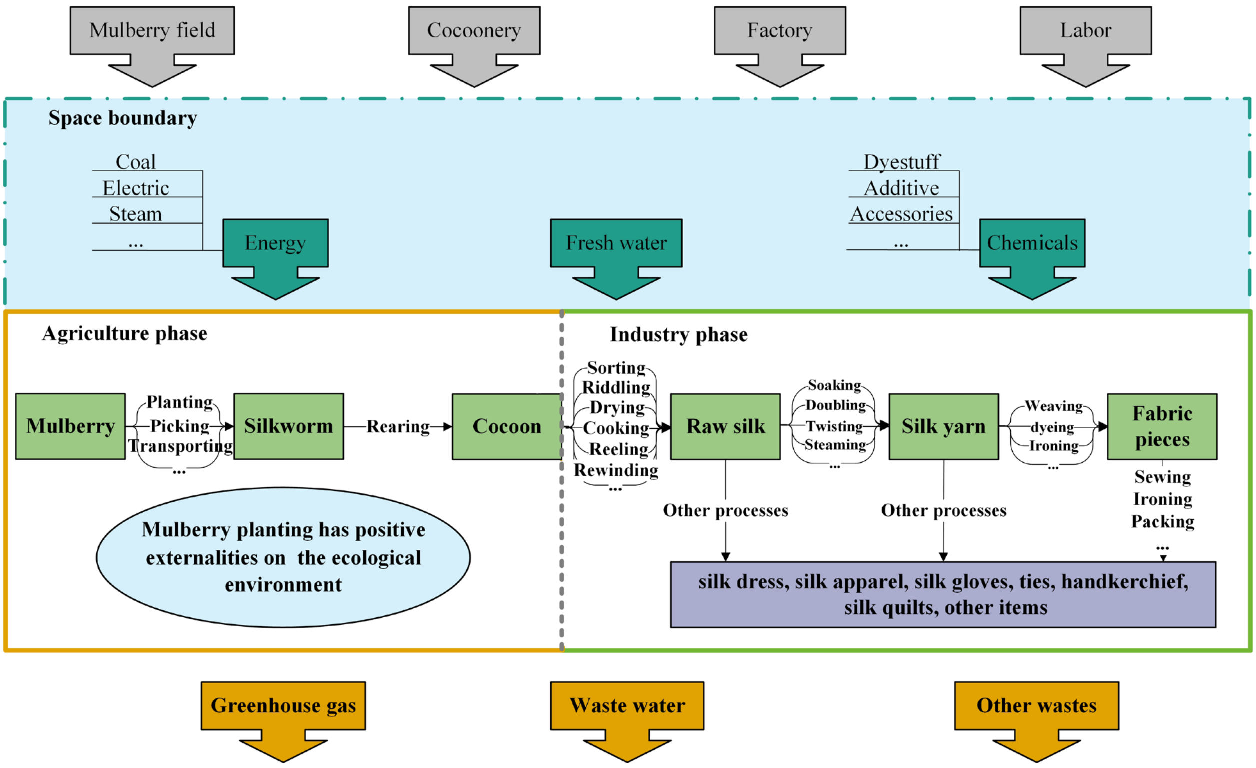

Fig. 2. Production process flow of silk products

The inconsistent results of carbon emissions during industrial production in the existing research are due to different research objects and inconsistent accounting boundaries. In the meantime, in order to evaluate the carbon emission of silk products at the stage of industrial production, it is necessary to clarify input and output data, such as electricity dissipation, heat consumption, water consumption, chemical consumption, auxiliary material consumption, output of silk products, etc. Because the level of production technology in different countries varies greatly, the carbon emission results of silk products at the stage of industrial production are quite different. Astudillo et al. [14] determined the carbon emission in the life cycle of one kilogram of raw silk as 80.9 kg CO_2eq. Compared with Chinese cotton, nylon 66 and wool, the results showed silk had a larger carbon emission across most categories assessed. However, the inventory data for this study came from a village in Karnataka, India, where rudimentary practices are adopted for cocoon and silk production. Therefore, some proportion of the carbon emission of silk can be attributed to inefficiencies in agricultural infrastructure, specifically electricity supply and irrigation. Moreover, in the absence of datasets specific to the manufacture of silk products, most data used in existing studies come from a database which is obsolete and inaccurate, resulting in widely divergent findings on carbon emission. What is more, emission factors required to calculate indirect emissions are incomplete, resulting in uncertainty in the final results of carbon emission. Taking the same product as the research object, the results of carbon emission vary greatly due to different accounting boundaries, the database, and carbon emission factors.

4. Carbon footprint of distribution and consumption

Finished silk products then enter the segments of distribution and consumption. In the distribution phase, both transportation and retail processes will produce carbon emission. The amount of carbon emission depends on the conveying distance, and the choice of transportation mode and retail mode [36]. Depending on the conveying distance, different modes of transport are used, such as maritime transport, land transport, air transport, etc. The transportation of silk products consumes large amounts of diesel fuel and creates carbon emission. The models of silk product retail can be divided into traditional retail and online retail. The energy used in stores is the major source of carbon emission for traditional retail [37]. Online retailing is becoming increasingly popular at present and studies illustrate that it can contribute to reducing carbon emission, due to lower energy use and carbon emission associated with transportation [38].

The use stage is critical in the life cycle of silk products, in which energy, detergent and water are used for the washing, drying, ironing and dry cleaning of silk products [39]. As is known to all, silk fabric is thin and fragile, as a result of which consumers tend to use lighter, less energy-consuming patterns during washing. Many silk products, such as ties, wallets and souvenirs, do not require frequent cleaning, and silk quilts have long life cycles and extremely low washing frequencies, resulting in a lower carbon dioxide emission during the washing process of silk products. Li et al. [40] calculated the carbon footprint of a garment during the cleaning procedure, the results of which showed that the carbon footprint of 1 kg of the garment is 0.0476 kg in the soft washing mode and 0.0208 kg in hand washing, while the carbon footprints of drying and ironing are 0.7333 kg and 2.3041×10^{-3} kg. As a result, the total carbon emissions of 1kg of silk garments during the cleaning procedure are 0.7832 kg. Another research showed that both cotton and synthetics were washed at a higher temperature and heavier laundry load than delicates such as silk [41]. Garments made of silk were almost three times more likely to be hand-cleaned than those of cotton or synthetics and their blends. Furthermore, compared with cotton and linen garments, silk ones require a lower ironing temperature and shorter preheating time, consume less energy, and produce less carbon emission. Accordingly, silk products require less energy and chemicals to be kept clean, thereby releasing less carbon , compared to products made from other fibers. Standard models of laundry times for different silk products need to be established on account of the diversity of washing times of silk products, so as to obtain specific results of the carbon footprint at the use stage of silk products and make the results more scientific and comparable.

5. Carbon footprint of the end of life stage

ISO 14067 specifies that the end of life stage begins when the product used is ready for disposal, recycling, reuse, etc [3]. Some of the obsolete silk products are landfilled directly instead of into cycles of recycling. Abandoned silk products will naturally disintegrate over time and release carbon dioxide fixed inside the products previously.

It is well known that recycling has both economic and environmental benefits. For example, by recycling 1 kg of used clothes, 6000 l of water consumption, 0.3 kg of of the fertilizers used, 0.2 kg of of the pesticides used, and 3.6 kg of CO_2 emissions can be reduced according to a study made at the University of Copenhagen [42]. Consequently, the recycling of waste silk products can save resources, and on the other hand make a good contribution to reducing carbon emission. Different recycling methods of waste silk products result in various amounts of carbon emission and carbon neutralisation.

In the present paper, recycling methods are divided into energy recycling and material recycling. Energy recycling refers to the incineration process of silk products, which may provide beneficial energy generation, where heat created by burning can be used to generate electricity so as to reduce the use of coal; but this must be carefully balanced with the potential for carbon emission [43]. Material recycling most often refers to the reprocessing of pre- or post-consumer waste silk products for use in new silk or other products [44]. Material recycling processes include monomer, oligomer and polymer recycling, fibre recycling or fabric recycling methods [45]. Used silk products can be cut into small pieces and then be used to make recycled products such as rugs, bags, accessories and wadding, which can effectively prolong the service life of silk products and reduce the use of raw silk and the emission of CO_2 [46]. The routes of material recycling are typically classified as being either mechanical, chemical or thermal. For example, the chemical recycling of silk products most often refers to a recycling route in which silk products are dissolved, disassembled to a molecular level, and re-spun into new fibres. The material recycling method is also shown to have negative carbon emission values, meaning that it is considered to avoid more carbon emission than it emits. Nevertheless, silk fabric is typically insoluble in a variety of solvents, which renders it challenging to recycle. Nowadays, new technologies for the recycling of waste silk products are being developed. A new recycling strategy was proposed to extract fibroin fibers from silk waste selvage to form well-defined fibroin nanofiber, which is of higher value than the original silk product [47]. Song et al. [48] used waste silk to produce functional paper which can reinforce plastic matrix. Using waste silk as the production material minimises the use of virgin materials and contributes to reducing carbon emission. Munasinghe et al. [45] highlighted that recycling has lower carbon emission than gasification and incineration; however, its energy consumption is high. Therefore, the material recycling process of waste silk also involves energy consumption, causes other environmental impacts and requires further researches to make it clear [49].

6. Conclusions and the way forward

Silk has been regarded as a highly valued textile fiber which exhibits properties unrivaled by any other natural fiber such as high tensile strength, elasticity, absorbency, and great dyeing properties. Since carbon emission is threatening the global climate, it is important to fully understand the carbon emissions of silk products during their life cycles and identify the main causes of emissions for future study. This study analysed the characteristics of various stages in the whole life cycle of silk products and conducted a systematic literature review that collated data on the carbon emission and neutrality which occur throughout the life cycle of silk products. The study shows that there is a positive correlation between cocoon acquisition and carbon footprint mitigation when computing the cultivation of mulberry trees. As a consequence, mulberry fields around the world have great carbon sequestration potential. Apart from the cocoon acquisition stage, carbon emissions at the stage of industrial production are also noteworthy. The industrial production of silk products is composed of many processes, such as spinning, weaving, cutting, sewing, etc. These processes consume electricity, which emits carbon dioxide during its production phase. Therefore, accelerating the development of wind power, solar power and other non-fossil energy generation plays an important role in reducing carbon emissions at the stage of industrial production. Furthermore, the phases of distribution and consumption generate carbon emission due to transportation, energy used in conventional retailing, and domestic washing. At the use phase, the types of appliances used can make a significant difference to the environmental impacts. Furthermore, the number of washing cycles operated during the user phase is critical since it affects the durability and increases energy use. Hence, reducing the number of washing cycles is conducive to decreasing carbon emissions at the washing stage. Also, standards on methods for assessing the impact of silk clothes laundry should be established in order to increase the comparability of studies. At the end of the life phase, the positive impact on carbon emission in the phase of recycling is noteworthy.

This review has highlighted that there is a lack of cases that consider carbon emission and carbon neutrality accounting for the whole life cycle of silk production. Moreover, there is scant carbon emission assessment study on the consumption and recycling processes of silk products in the existing literature. Consequently, if we need more accurate carbon footprint results of silk products, life cycle inventory data on energy use, water use, carbon emission and carbon neutrality for a range of materials across all stages of the life cycle are required. For future studies, it is proposed to establish a more reasonable model of washing cycles and conduct a more complete carbon footprint assessment during the whole life cycle of silk products to promote the sustainable development of the silk industry.

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