Quantification and analysis of carbon neutralization in mulberry and silk in China

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ABSTRACT – REZUMAT

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With the concern of global warming, efforts are increasingly focused on understanding and addressing carbon emission in the life cycle of silk products. Whereas, the carbon sequestration effects of mulberry and silk are rarely mentioned in the previous studies on the carbon footprint of silk products. In this regard, this study constructed a biomass method to adequately evaluate the carbon sequestration effects of mulberry and silk produced in China. An application demonstration was conducted in the area of mulberry fields and the cocoon yield of the silk industry in China from 1990 to 2021. The results indicate that mulberry fields in China fixed 875.9608 million tons of CO_2 from 1990 to 2017, while silk in cocoons produced in China fixed a total of 5.9528 million tons of CO_2. These vast quantities of carbon trapped in mulberry leaves enter the silk, the silkworm chrysalis and silkworm droppings, as well as other by-products as silkworms ingest, grow, and spin cocoons. This demonstrates that increased exploitation of sericulture by-products can also contribute to carbon sequestration. Besides, the influence of the silk product's lifespan should be taken into account when quantifying and analysing the carbon neutralization of silk. Therefore, extending the usage life of silk products as long as feasible can also have a great effect on the carbon sequestration of silk products.

Keywords: *carbon storage, carbon neutralization, mulberry, silk, temporary carbon storage effect*

Cuantificarea și analiza neutralizării carbonului la duzi și mătase în China

Cu preocuparea încălzirii globale, eforturile sunt din ce în ce mai concentrate pe înțelegerea și abordarea emisiilor de carbon în ciclul de viață al produselor din mătase, întrucât efectele de captare a carbonului ale dudului și mătăsii sunt rareori menționate în studiile anterioare, privind amprenta de carbon a produselor din mătase. În acest sens, acest studiu a construit metoda biomasei pentru a evalua în mod adecvat efectele de captare a carbonului din duzii și mătasea produsă în China. O demonstrație a aplicației a fost efectuată cu zona câmpurilor de dud și a producției de cocon din industria mătăsii din China din 1990 până în 2021. Rezultatele indică faptul că în general, câmpurile de dud din China au fixat 875,9608 milioane de tone de CO_2 între 1990 și 2017, în timp ce mătasea din coconi a produs în China un total de 5,9528 milioane de tone de CO_2. Aceste cantități uriașe de carbon prinse în frunzele de dud intră în mătase, în crisalida și excrementele de viermi de mătase, precum și în alte produse secundare pe măsură ce viermii de mătase ingerează, cresc și învârt coconii. Acest lucru demonstrează că exploatarea sporită a produselor secundare de sericicultură poate contribui, de asemenea, la captarea carbonului. În plus, influența duratei de viață a produsului de mătase trebuie luată în considerare la cuantificarea și analizarea neutralizării carbonului din mătase. Prin urmare, prelungirea duratei de utilizare a produsului de mătase, atâta timp cât este fezabil, poate avea, de asemenea, un efect semnificativ asupra captării carbonului din produsele din mătase.

Cuvinte-cheie*: depozitarea carbonului, neutralizarea carbonului, dud, mătase, efect de stocare temporară a carbonului*

INTRODUCTION

China is the largest producer and the leading supplier of silk in the world with 53369t/y in 2020 [1]. The production processes, reeling of raw silk, processing of silk yarns into fabrics, dyeing, finishing and manufacturing of products, involve a substantial amount of electricity, steam, fossil fuels, fresh water, chemicals, and packaging materials, and are blamed for producing significant amounts of greenhouse gas (GHG) [2]. According to the comparative research carried out by the Waste & Resources Action Program (WRAP) [3], from cocoon production to the end of life, each ton of silk fibre produced a carbon footprint of 25.425 kg CO_2e. Apart from that, some studies investigated the carbon footprint of silk manufacturing. Barcelos et al. [4] analysed the life cycle assessment (LCA) of the core processes of mulberry and silk cocoon production and evaluated the carbon footprint in the production process. Astudillo et al. [5] conducted the life cycle assessment of raw silk, in which the carbon footprint of mulberry production, silkworm rearing, cocoon drying, and cocoon reeling was evaluated. Ren et al. [6] studied the environmental impact of 100 kg silk textiles and analysed the global warming potential. Jiang et al. [7] introduced the carbon footprint assessment of gambiered canton silk and demonstrated that the total carbon footprint per meter of fabric was 1.88 kg CO_2e. Faragò et al. [8] calculated the environmental impact of yarn-dyed silk fabrics, printed silk fabrics and dyed silk fabrics, and analysed global warming potential (GWP).

In the long production process of silk, mulberry leaves are the raw material and essential components for the front-end process. Over 90% of commercially produced silk is spun by the domesticated silkworm, a monophagous insect whose diet is restricted to the leaves of the mulberry tree [5]. As a fast-growing tree, mulberry starts to produce commercial quantities of leaves for the cultivation of silkworms within one year of planting [9]. Mulberry, as a consequence, has a high capacity for carbon sequestration, which refers to the ability to remove CO_2 from the atmosphere [10]. Due to its high ecological and socioeconomic versatility, and particularly its great potential for carbon sequestration, mulberry has been receiving increasing attention in recent decades. According to research conducted by Giacomin et al. [11], approximately 81.65 tons of CO_2 are fixed in one hectare of mulberry per year, of which 64.80 tons are fixed in mulberry leaves, branches and other above-ground parts, and the remaining 16.80 tons are kept below ground level for quite a long time. In 2020, mulberry orchards occupied 807847 hectares in China, and it can be estimated that Chinese total mulberry fields can fix 65.96 million tonnes of CO_2 annually. Garcia Jr et al. [11, 12] pointed out that mulberry trees have a significant potential for carbon mitigation. Srikantaswamy and Bindroo [13] claimed that the production of mulberry biomass offered appealing properties for carbon sequestration due to its rapid growth and wide adaptability. Research conducted in 2020 found that mulberry cultivation had a negative net carbon emission, suggesting that the carbon emission was less than the photosynthetic carbon sink and that mulberry production had a positive ecological externality [14]. From this perspective, mulberry planting can contribute carbon neutrality to the production of silk [15].

Mulberry synthesizes water and carbon dioxide into carbohydrates by photosynthesis. Some of these carbohydrates are consumed as plant respiration and the other part is converted into branches, leaves, roots, etc. When the silkworm matures and spins cocoons, the carbon trapped in mulberry leaves enters the silk. As a consequence, silk has a carbon sequestration effect and carbon neutralization potential. However, in the previous research, the carbon sequestration effects of mulberry and silk are not thoroughly investigated. Few studies took the carbon mitigation made by mulberry into account to evaluate the carbon footprint of silk. In this regard, this study constructed a biomass method to adequately evaluate the carbon sequestration effects of mulberry and silk from the standpoint of raw materials of silk. In this paper, the carbon sequestration of mulberry and silk was examined from macro and micro perspectives respectively. The carbon sequestration of silk was obtained innovatively by analysing the flow of dry matter sequestered by mulberry leaves during the life cycle of silkworms, and the duration of carbon storage and delayed GHG emissions were considered. These efforts enriched the knowledge of carbon footprint and quantified carbon neutrality in silk.

Besides, an application demonstration was conducted in the area of mulberry fields and the cocoon yield of the silk industry in China from 1990 to 2017 to provide a reference for the carbon sequestration effect assessment of mulberry and silk.

METHODOLOGY AND DATA

Carbon sequestration model of mulberry field

Silk has been regarded as a highly valued textile fibre and is favoured by consumers all over the world. As a result of the demand for silk, mulberry fields flourished. Due to its rapid growth rate and robust yearly regeneration following harvesting, the mulberry field has a significant carbon storage potential. The carbon sequestration coefficient of mulberry fields per hectare has been calculated in previous studies [11, 12, 16]. The total carbon storage of mulberry fields can be obtained by multiplying the total planting areas by the coefficient of carbon sequestration, as shown in equation 1.

$$Q_{CO_2} = \gamma \times S \times 44/12 \qquad (1)$$

where, Q_{CO_2} is the total CO_2 storage (t), γ – the coefficient of carbon sequestration, S – the total planting areas (hm^2), 44 – the mole mass of CO_2, 12 – the mole mass of C.

Carbon sequestration model of dry biomass

Mulberry trees synthesize CO_2 into carbohydrates through photosynthesis during their growth process. These carbohydrates are stored in mulberry leaves and support silkworm consumes, growing, and spinning cocoons. The sequestered carbon does not return to the atmosphere before the silk is degraded or burned. The carbon neutralization effect of silk can be quantified using the dry-weight biomass method currently. The dry weight biomass method chiefly calculates CO_2 sequestration based on the changes of biomass indirectly [17]. Biomass multiplied by the carbon coefficient in the dry matter can be converted into carbon storage, as shown in equation 2:

$$Q_{CO_2} = m_{bio} \times (1 - R_{H_2O}) \times R_c \times 44/12 \qquad (2)$$

where, Q_{CO_2} is the total CO_2 storage (t), m_{bio} – the weight of biomass consumed (kg), R_{H_2O} – the content of H_2O, R_c – the content of C, 44 – the mole mass of CO_2, 12 – the mole mass of C.

Data sources

China produces more than 80% of the world's cocoon and raw silk in 2019 [18]. The data used for the carbon sequestration accounting were collected from the Silk Yearbook of China (2000–2018), which

Table 1

AREA OF MULBERRY ORCHARDS AND OUTPUT OF SERICULTURE PRODUCTS IN CHINA FROM 1990 TO 2021						
Year	**Mulberry field area (hm^2)**	**The output of mulberry Leaf (ten thousand tonnes)**	**The output of mulberry branch (ten thousand tonnes)**	**The output of silkworm cocoon (tonne)**	**The output of cocoon shells (tonne)**	**The output of silkworm chrysalis (tonne)**
1990	484069.09	1452.20	580.88	480179.00	120044.75	360134.25
1991	1026671.80	3080.00	1232.00	511517.00	127879.25	383637.75
1992	1252806.26	3758.40	1503.36	610250.00	152562.50	457687.50
1993	1249739.58	3749.20	1499.68	619800.00	154950.00	464850.00
1994	1244826.22	3734.46	1493.78	673952.00	168488.00	505464.00
1995	1163139.15	3489.40	1395.76	656365.00	164091.25	492273.75
1996	864870.99	2594.60	1037.84	403387.00	100846.75	302540.25
1997	638469.86	1915.40	766.16	404885.00	101221.25	303663.75
1998	626203.13	1878.60	751.44	432821.00	108205.25	324615.75
1999	579602.90	1738.80	695.52	409021.00	102255.25	306765.75
2000	632436.50	1897.30	758.92	454614.30	113653.58	340960.73
2001	721016.94	2163.04	865.22	512707.68	128176.92	384530.76
2002	769083.85	2307.24	922.90	515884.85	128971.21	386913.64
2003	765737.16	2297.20	918.88	481470.15	120367.54	361102.61
2004	781110.57	2343.32	937.33	547091.30	136772.83	410318.48
2005	773643.87	2320.92	928.37	616145.00	154036.25	462108.75
2006	855684.28	2567.04	1026.82	739715.34	184928.84	554786.51
2007	922624.61	2767.86	1107.14	782098.21	195524.55	586573.66
2008	878904.39	2636.70	1054.68	677648.17	169412.04	508236.13
2009	810770.72	2432.30	972.92	649107.06	162276.77	486830.30
2010	802057.34	2406.16	962.46	667239.74	166809.94	500429.81
2011	827450.80	2482.34	992.94	654989.50	163747.38	491242.13
2012	841644.21	2524.92	1009.97	643024.03	160756.01	482268.02
2013	839304.20	2517.90	1007.16	641006.41	160251.60	486225.00
2014	828244.14	2484.72	993.89	641006.40	160251.60	480754.80
2015	821310.77	2465.00	985.57	628210.00	157052.50	478428.75
2016	793110.63	2379.32	951.73	620406.00	155101.50	465304.50
2017	788723.94	2366.16	946.46	643114.00	160778.50	482335.50
2018	789943.95	2369.82	947.93	679038.00	169759.50	509278.50
2019	755277.11	2265.82	906.33	720805.00	180201.25	540603.75
2020	807850.71	2423.54	969.42	687178.00	171794.50	515383.50
2021	796700.00	2390.08	956.04	717200.00	179300.00	537900.00

reported mulberry leaves yields and mulberry field area, as well as the amounts of various sericulture outputs including silkworm cocoons, cocoon shells and silkworm chrysalis in China. The specific data are shown in table 1 [19].

RESULTS AND DISCUSSION

The yearly carbon sequestration of mulberry fields and silk in China was calculated according to equation 1 and equation 2 in the Methodology section respectively. The results are depicted in figure 1 and figure 2.

As shown in figure 1, the carbon sequestration of mulberry fields calculated with γ_1 was the largest, and followed by γ_2. These two coefficients of carbon sequestration were referred to the research of Garcia Jr (γ_1) and National Forestry and Grassland Administration (γ_2). The results calculated using coefficient γ_2 are primarily analysed in this study. The quantity of CO_2 sequestered by mulberry fields increased from 1990 to 1992. It reached 4653.34 million tons in 1992 with an increase of 158.81% compared to the quantity in 1990. Since 1992, the quantity of CO_2 sequestered by mulberry fields showed a slow downward trend until 1995 and began to decline sharply, reaching the lowest point in 1999. The quantity of CO_2 sequestered by mulberry fields increased again from 1999, rising to a peak value of 34.2694 million tons in 2007. Following a slight decline between 2007 and 2010, the quantity of CO_2 sequestered by mulberry fields has been stable since

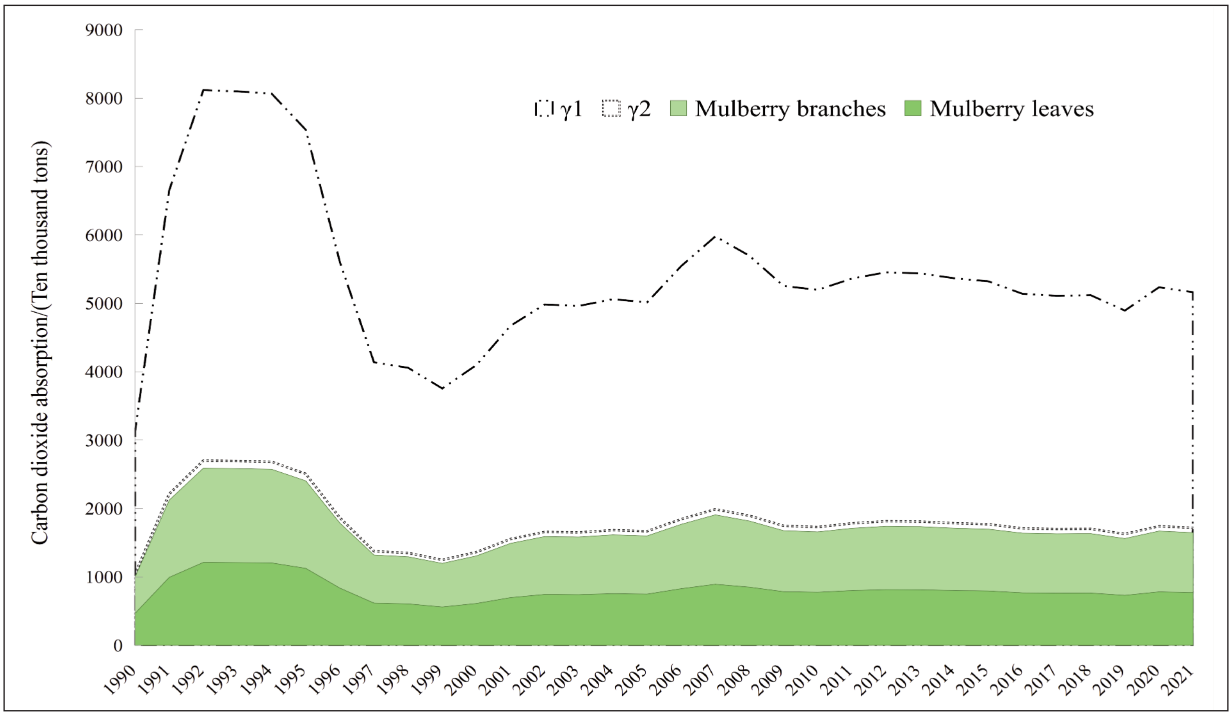

Fig. 1. Carbon sequestration of mulberry fields in China from 1990 to 2021

2010. The amounts of CO_2 immobilized by mulberry leaves and branches sequestered were 26.06% and 29.61% of the total CO_2 sequestered by mulberry fields respectively. They showed the same variation trend as that of CO_2 immobilized by mulberry fields.

Since the economy reformed and opened up, the government has been attaching continuous importance to the restoration and development of sericulture production. In the late 1980s, the popularity of natural fibres under the increasing environmental protection awareness led to a boom in silk consumption, which greatly increased the demand for silk in the international markets. The soaring price of cocoon further stimulated the enthusiasm of sericulture production throughout the country. The area of mulberry fields increased gradually to 1252806 hectares in 1992. However, the demand for silk products all over the world did not increase synchronously with mulberry fields, so the cocoons were overstocked. The cocoon price declined from the second half of 1995. Besides, the enthusiasm of silkworm farmers was severely dampened. Hence, lots of farmers left sericulture for other crops or went to cities to make money, resulting in a substantial decrease in mulberry fields and cocoon production in 1996. The government took measures to regulate the sericulture industries including cocoon production, reeling and weaving from 1996. Therefore, the decline rate of the area of mulberry fields slowed down from 1996 to 1999. After a ten-year adjustment and reform of the mulberry and cocoon industry, sericulture areas shifted from developed regions in eastern China to developing regions in southwestern China. In the developing regions, sericulture areas are expanding because of their low labour costs and stable income. With the increasing demand for silk products in the global market, the area of mulberry fields started to increase from 2000, until the outbreak of the global financial crisis in 2008. The demand for silk products in the global market declined as a result of the financial crisis, and the area of mulberry fields shrunk marginally. The global economy has progressively recovered since 2010, and the area of mulberry garden fields has shown signs of stability.

Figure 2 shows that the quantity of CO_2 sequestered by raw silk also grew at first (1990–1994), then reduced sharply (1994–1996), and then climbed again (1996–2008). Nevertheless, unlike the variation of mulberry orchards, the output of cocoon increased significantly in 2007 compared to the previous peak in 1994 due to the development and application of advanced sericulture technologies.

Meanwhile, the amount of CO_2 immobilized by cocoon shell and silkworm chrysalis accounted for 46.08% and 53.92 % of the total CO_2 sequestered by cocoon respectively (figure 3).

The annual amount of CO_2 sequestered by mulberry fields is significantly larger than that sequestered by silk. Figure 3 depicts the flow of dry matter fixed in mulberry leaves during the silkworm's life cycle. Taking one silkworm as the research unit, the total dry matter of mulberry leaves eaten by a silkworm in its whole life cycle is 5 grams, of which 62% is discharged by the silkworm in the way of silkworm droppings, and the rest is digested by the silkworm. The silkworm consumes 46% of the 1.9 grams of dry matter which it digests for energy consumption during the evolution stage, 7.3% for silk synthesis, 21% for pupae formation and 25.5% for cocoon shell forma-

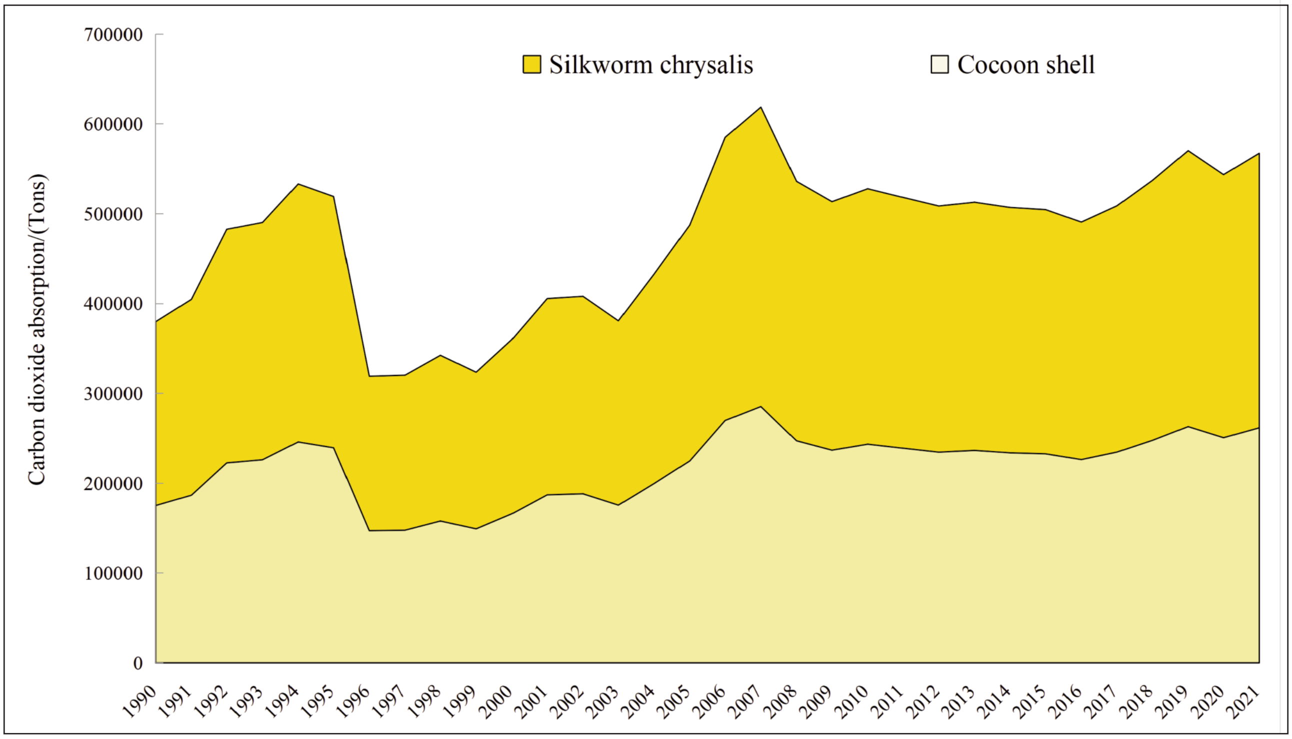

Fig. 2. Carbon sequestration of cocoons in China from 1990 to 2021

tion. It can be seen that in addition to the cocoon shell utilized for silk reeling, a significant quantity of carbon is also fixed in silkworm pupae and silkworm droppings. This demonstrates that using by-products generated from sericulture is also helpful to fix CO_2. The by-products of sericulture such as silk sericin, silkworm droppings and waste silk can be processed and utilized with new and high technologies [20]. For example, after drying at high temperatures, silkworm droppings can be mixed with other therapeutic ingredients to make a pillow conducive to sleep and good for human health. The pillow contains a significant quantity of biological carbon, which helps to offset the carbon produced by the sericulture. When silk by-products are not used and discarded instead, they spontaneously dissolve, releasing the carbon that was trapped in the material. Applications of sericulture by-products could decrease raw material waste and environmental effects, as well as generate employment and income [21].

Once captured and stored by mulberry trees, enters the silk through the consumption of silkworms, and

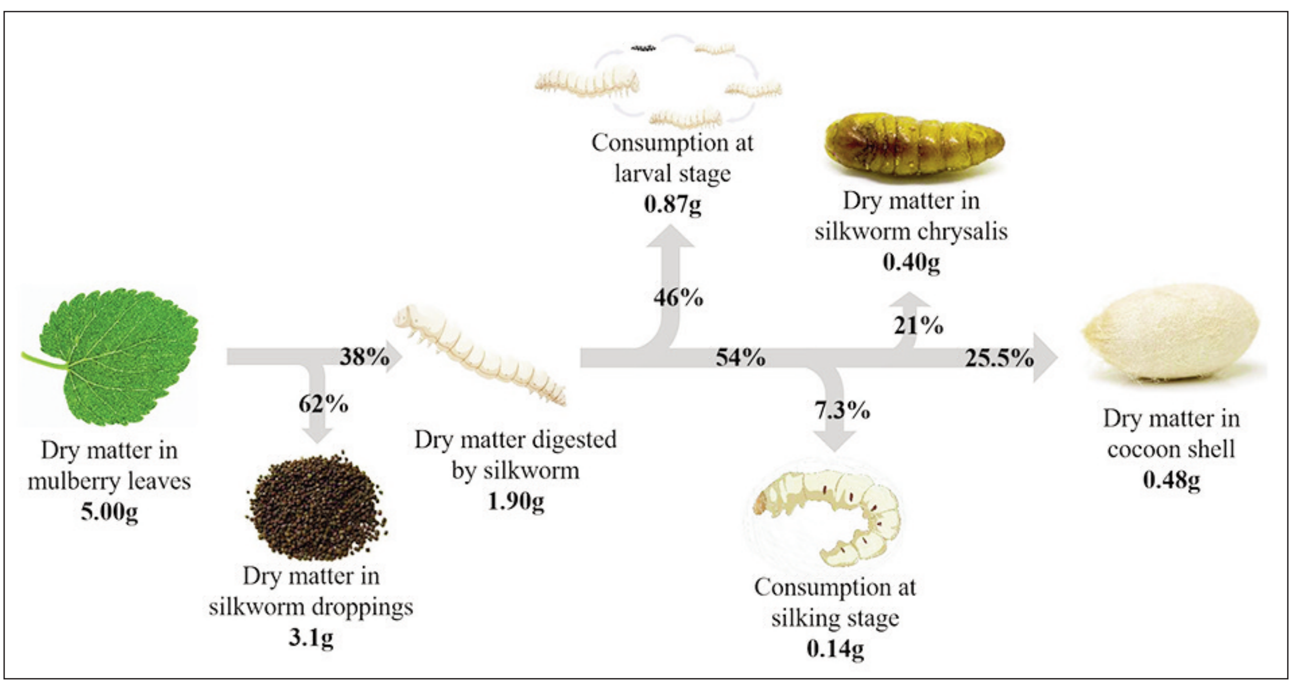

Fig. 3. The flow of dry matter sequestered by mulberry leaves during the life cycle of silkworms

carbon will reenter the atmosphere sooner or later after the use phase of the silk products [22]. As a result, the service cycle of silk products should be considered when quantifying and analysing the carbon neutralization of silk. Carbon sequestration during biomass growth can be accounted for as a negative carbon emission in LCA, but the duration of carbon storage and delayed GHG emissions are usually not taken into account. According to PAS 2050 [23], the later GHG emissions occur, the shorter their residence time in the atmosphere and the smaller their impact on global warming in a 100-year time horizon. It is not until emissions occur after 100 years that their impact will become zero. According to the findings of Giacomin et al. [11], one hectare of mulberry trees fix about 81.65 tons of CO_2 per year, of which 16.80 tons are kept below ground level for a considerable amount of time. The carbon footprint for producing per ton of silk fibre is 25425 kg of CO_2 equivalent from the production of cocoons to the end of life, and silk fibre production per hectare was 111 kg, resulting in a carbon footprint of 2.82 tons/ha. As a result, the amount of CO_2 that is kept below ground level for an extended period per hectare is around six times the amount of CO_2 that will be left by fibre silk produced in the same hectare. From this perspective, mulberry planting can contribute carbon neutrality to the production of silk in a 100-year time horizon. Besides, the effect of carbon sequestration is affected by the duration of silk products. The longer the product is used, the more significant the effect of carbon sequestration will be. Accordingly, when using silk products, consumers should pay attention to reusing and recycling the product to extend the period of carbon storage as long as possible [24].

Abandoned silk products will naturally disintegrate over time and release carbon sequestered inside the products. As a result, proper recycling is a crucial way to carbon neutralization of silk. Obsolete products made from silk can be broken down into smaller units and converted into carpets, bags, accessories, wadding and other recyclable items, thereby extending the service life of products and reducing raw materials consumption and CO_2 emissions [25]. At the same time, once the service life of products made from silk has expired, energy recovery can be carried out, which refers to the incineration process of the products. The energy recovery of products can offer advantageous energy generation [26]. The heat generated by combustion can be utilized to generate electricity, reducing the usage of coal and, on the other hand, minimizing CO_2 emissions.

CONCLUSIONS

As an important material basis for silk production, mulberry trees synthesize CO_2 into carbohydrates through photosynthesis during their growth process, which is a key factor in mitigating increased CO_2 in the atmosphere. Simultaneously, the carbon in mulberry leaves will be fixed in cocoon shells, silkworm chrysalis, silkworm droppings, and other by-products as a result of the life activities of silkworms. In this paper, the carbon neutralization effects of mulberry and silk in China were explored. Given the results found in this study, it would be recommendable to consider the service cycle when quantifying and analysing the carbon neutralization of silk products. The longer the silk product is used, the more significant the effect of carbon sequestration will be.

It is noteworthy that the lifespan of various silk goods varies. From an accurate assessment perspective, specific life cycle models should be constructed to evaluate the carbon sequestration effects of different silk products in future research.

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