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Carbon Neutrality Potential of Textile Products Made from Plant-Derived Fibers

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Abstract: During the growth of biomass, there are two carbon storage paths for plant-derived fibers. One path is to assimilate carbon dioxide (CO_2) from the atmosphere through photosynthesis and temporarily store it in textile plants. Besides, the carbon can be captured and stored in soil. The carbon storage capacity of textile products made from plant-derived fibers such as cotton, flax, hemp, kenaf and bamboo fiber, etc., is a non-negligible part of greenhouse gas (GHG) accounting and reporting. However, there is a lack of systematic methods to evaluate carbon storage and the delayed emission effect of plant-derived fibers. In this study, the carbon storage and emission times of 100% hemp T-shirt, 100% hemp slipcover, and 100% hemp fiber handicraft were evaluated by using the soil organic carbon method, dry weight biomass method, and modeling method. The results revealed that the CO_2 storage of 1 kg hemp fiber is 1.833 kg. Meanwhile, the delayed emission effects of carbon temporarily stored in the 3 kinds of hemp fiber products are 3.83%, 19.68%, and 41.12% at different lifespans (i.e., 5, 25, or 50 years), in which case the landfill option for hemp fiber products may be preferable from carbon storage effect perspective. The results suggest that plant-derived fibers have a positive impact on climate change due to CO_2 storage, and that the carbon storage effect improves with the continued lifespan of the product. By quantifying carbon storage and the delayed emission effect of plant-derived fibers, it is beneficial to understand the potential for reducing carbon emissions, which in turn helps to promote and develop more environmentally friendly and low-carbon production processes and products.

Keywords: carbon storage; carbon footprint; temporary carbon storage effect; plant-derived fibers; textile products

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1. Introduction

The carbon activities related to the production of textile products includes two categories: one is carbon sink (carbon storage) activities, and the other is carbon sources (carbon emission) activities. For greenhouse gas (GHG) emissions, textile products are accused of producing significant amounts of GHG in industrial production [1]. It is roughly estimated that the textile sector is responsible for 1 ton of every 19.8 tons of total CO_2 emissions in the environment [2]. However, in addition to the life cycle of GHG emissions, textile and garment products made from plant-derived fibers (e.g., cotton, flax, hemp, kenaf, and bamboo fibers) have an excellent carbon storage effect, which refers to the ability to remove CO_2 from the atmosphere [3].

There are two carbon storage paths for plant-derived fibers. One path is to synthesize CO_2 into carbohydrates through photosynthesis during growth, which is a key factor in combating the increased levels of CO_2 in the atmosphere. Guest et al. [4] investigated how the climate benefits of biochar stored in sustainably grown plants can be included in the life cycle assessment (LCA). Muthu et al. [5] pointed out that the amount of CO_2 absorbed during the fiber production phase contributes to offset global warming. Yang et al. [6] measured and analyzed the carbon footprint of hemp fiber throughout its life cycle from cultivation to end product according to PAS 2050 [7] and found that hemp has carbon storage benefits during cultivation. Besides, carbon can be stored in soil through improved cropland management practices, such as the application of organic manure and cover crops, improved crop rotations, bare fallow reduction, and more efficient irrigation management [8]. Shen et al. [9] investigated that soil organic carbon (SOC) increases of 25.8 t ha^{-1} are observed over 100 years when hemp stems (straw) are left on carbon-vulnerable land (CV-lands). Liu et al. [10] studied the soil organic carbon density under continuously cropped cotton in China's Xinjiang Province. The results showed that soil organic carbon density increased with time in the straw-incorporated treatment, but decreased with time in the straw-removed treatments.

Indeed, carbon storage in plant and soil during growth can be accounted for as a negative emission in carbon footprint, but the duration of carbon storage and delayed emissions in products are typically ignored. This is because the atmospheric concentration is dictated by the interactions between anthropogenic CO_2 emissions and storage, as different times with respect to the emission of carbon will result in different trajectories of atmospheric CO_2 concentrations and thus variable cumulative radiative forcing [3]. The later that carbon emissions occur, the shorter their residence period in the atmosphere and the lower their influence on global warming over a 100-year time horizon, according to PAS 2050 [7]. It is not until emissions occur after 100 years that their impact becomes zero. Therefore, the effectiveness of carbon storage is influenced by the duration of product. The longer the lifespan of a product, the more effective the carbon storage will be.

CO_2 is separated from the atmosphere during the plant growth phase and remains separated during the lifetime of a product made of components of the plant. Subsequently, it will release back to the atmosphere when the biomass decomposes or is combusted [11]. Finkbeiner et al. [12] indicated that the way biogenic carbon is handled also affects the carbon footprint of products. The biogenic carbon is assumed to be emitted as CO_2 based on the combustion scenario. In contrast, biogenic carbon that does not degrade remains stored during a landfill scenario, while the degradable fraction of biogenic carbon contained in the disposed product can be emitted as CO_2 and CH_4 into the atmosphere [13]. Therefore, it is vital to quantify and compare the effect of biogenic carbon storage under certain waste management.

LCA has been applied extensively as an effective tool to evaluate the environmental impacts of the textile sector and it is considered as an objective approach to quantifying the GHG emissions of the production process [14]. When LCA is applied only to the environmental impact related to global warming (the greenhouse effect), it is called the carbon footprint [15]. However, there is currently no consensus in carbon footprint assessment studies on how to quantify the carbon storage in soil and the temporary carbon storage effects of textile products made from plant-derived fibers. Kirschbaum [16] pointed out that temporary carbon storage only reduces climate-change impacts related to the cumulative effect of increased temperature, but worsens other climate-change impacts. Additionally, ISO 14067 and the Greenhouse Gas (GHG) Protocol currently do not provide any standardized method for assessing the effects of temporary carbon storage, which advise that biogenic CO_2 storage in products shall be reported separately in the carbon footprint study report and not included in it [17]. As for PAS 2050 [7], the portion of biogenic CO_2 not emitted to the atmosphere during the 100-year assessment period is treated as the biogenic CO_2 storage effect and is accounted for in the carbon footprint assessment.

In this regard, this paper calculated the carbon storage in plant and soil during the cultivation phase of plant-derived fibers. Additionally, the robust model was described and constructed for assessing the effect of temporary carbon storage with product lifespan and studied the effect of carbon storage of products in their end-of-life phase. This study fills the gap in the research of carbon storage quantification and delayed emission effect of plant-derived fibers. Hemp fiber was chosen as the research object because it is a typical plant fiber found from the stem of the hemp plant and has carbon-storage capacity, higher biomass output, and various end-use products [18]. Furthermore, hemp is considered as a preferential cellulosic raw material as cultivation results in CO_2 storage, and it requires less water, fertilizers, pesticides, and herbicides than other plant-derived fibers [19]. A case study was implemented to evaluate the carbon storage and temporary carbon storage effects of three 100% hemp fiber products, and also to provide a reference for future carbon footprint systematic assessment of plant fiber products.

2. Materials and Methods

2.1. Carbon Storage Quantification

2.1.1. Carbon Storage in Soil

Generally, the management mode of the farmland where the plant-derived fiber is located is no more than 20 years. As a result, the soil carbon storage can be calculated according to IPCC [20], as shown in the following equation:

$$C_{soil} = [(SOC_E - SOC_O) \div D \div 365] \times T \times 44/12 \tag{1}$$

$$SOC_i = SOC_{ref} \times F_{LU} \times F_{MG} \times F_I \times A \tag{2}$$

where C_{soil} is the change of soil organic carbon pool during the growth period of plant-derived fiber (kg CO_2/mu), SOC_E is the soil organic carbon pool in the last year of the accounting period (kg C), SOC_O is the soil organic carbon pool in the initial year of the accounting period (kg C), D is the time for soil organic carbon pool to reach stability (year), T is the growth cycle of plant-derived fiber (day), 44 is the mole mass of CO_2, 12 is the mole mass of carbon, SOC_{ref} is the reference value of soil carbon pool content (kg C/mu), F_{LU} is the reservoir change factors of land use system (dimensionless), F_{MG} is the reservoir change factor of land management (dimensionless), F_I is the reservoir change factor of organic matter input (dimensionless), and A is the land area (mu).

2.1.2. Carbon Storage in Plant

Currently, the carbon neutralization effect of plant-derived fibers based on photosynthesis can be quantified by using the dry weight biomass method and photosynthetic rate method. The dry weight biomass method chiefly calculates the CO_2 storage based on the change of plant biomass indirectly [21]. The biomass of the stem and branches determines most of the CO_2 storage in the contribution of plants [22]. The photosynthetic rate method is developed by measuring the net photosynthetic rate per leaf area of a plant to obtain the net assimilation per plant leaf area per day [23]. The net photosynthesis rate of plants can reflect the carbon storage rate and the amount of CO_2 storage can be calculated from the net assimilation of plants [24].

The dry weight biomass method is based on the variation of plant biomass and the operation of this method is simple and straightforward. Meanwhile, its results are easier to quantify, and the margin of error is minimal. On the contrary, the photosynthetic rate method has an intricate and complicated experimental procedure, the amount of data required for the experiment is huge, and the outcomes are exceedingly ambiguous [23]. Therefore, the dry weight biomass method is preferred in this study to analyze the CO_2 storage in fiber plants.

Biomass multiplied by the carbon coefficient in dry matter can be converted into carbon storage [25]. The total carbon storage can be obtained by multiplying the total planting area by the average biomass per unit area and then by 0.5 (the average carbon content rate recommended by Solomon [26]), as shown in the following equation:

$$Q_{CO_2} = A \times B \times 0.5 \times 44/12 \tag{3}$$

where Q_{CO_2} is the total CO_2 storage (t), A is the total planting area (hm^2), B is the average biomass per unit area (t/hm^2), 44 is the mole mass of CO_2, and 12 is the mole mass of carbon.

This method is suitable for the majority of plant-derived fibers to calculate the total CO_2 storage [6].

2.2. Temporary Carbon Storage Effects

The decay function for CO_2 in the atmosphere is the basis for the calculation on carbon storage, which can be defined as the following equation according to Solomon [26]:

$$d(t) = a_0 + \sum_{i=1}^{3} [a_i \times \exp(-t/\tau_i)] \tag{4}$$

where a_0, a_i, and τ_i are the specific coefficients and time constants for three removal processes (i.e., i = 1, 2, 3), and t is the elapsed time (years). The values for the parameters in Equation (4) are shown in Table 1.

Table 1. Parameters of the decay function for CO_2.

Coefficients	Time Constants (Years)
$a_0 = 0.217$	
$a_1 = 0.259$	$\tau_1 = 172.9$ years
$a_2 = 0.338$	$\tau_2 = 18.51$ years
$a_3 = 0.186$	$\tau_3 = 1.186$ years

The GWP100 was the most popular metric to assess GHG emissions in the carbon footprint. According to PAS 2050 [7], the time boundary was determined to be 100 years (conventionally T = 100) after the formation of the product in the carbon footprint assessment of textile products. The 100-year (time horizon) plays a fundamental role in the calculation of the effect for carbon storage. As a result, the temporary carbon storage effect (years) of the GWP of plant-derived textile products within the accounting time (TH = 100 years) can be described by Equation (5), according to Clift and Brandão [27]:

$$GWP_{storage\ factor} = \frac{I_{t_0}}{I_{TH}} = \frac{\int_{TH-t_0}^{TH} d(t)dt}{\int_0^{TH} d(t)dt} = \frac{a_0 t_0 + \sum_{i=1}^{3} a_i \tau_i \left[\exp\left(\frac{t_0 - TH}{\tau_i}\right) - \exp\left(\frac{-TH}{\tau_i}\right)\right]}{a_0 TH + \sum_{i=1}^{3} a_i \tau_i [1 - \exp(-TH/\tau_i)]} \tag{5}$$

where t_0 is the delay in emission of CO_2 (years), $I(t_0)$ is the GWP reduction within the accounting time when the emission is delayed by t_0 years, and I_{TH} is the GWP over the accounting time.

By inserting the values for TH = 100, = 47.8, the approximate expression for Equation (5) can be described by Equation (6).

$$GWP_{storage\ factor} = \frac{I_{t_0}}{I_{TH}} = \frac{0.364 t_0 + 4.6 \times 10^{-4} {t_0}^2}{47.8} \approx 0.0076 t_0 \tag{6}$$

For the temporary biogenic carbon storage effect, the weighting factor (WF) is used to reflect the proportion of emission impacts that occur over the 100-year assessment period, which can be derived from Equation (7).

$$WF = \begin{cases} 1 - 0.0076 t_0, \text{ for } 2 \le t_0 \le 25 \\ \frac{\sum_{i=1}^{100} X_i \times (100-i)}{100}, \text{ for } t_0 = 1 \text{ or } t_0 > 25 \end{cases} \tag{7}$$

where i is the year in which emissions occur, and X_i is equal to the proportion of total storage carbon remaining in any year i.

The quantity of carbon stored is multiplied by this WF to calculate the benefit of storage. The effect of carbon storage is calculated using Equation (8).

$$\text{Carbon}_{\text{storage effect}} = Q_{CO_2} \times WF \tag{8}$$

where the $\text{Carbon}_{\text{storage effect}}$ is the effect of temporary carbon storage for t_0 years (kg CO_2 eq/kg biomass). According to different years of delayed emissions, the carbon released in the use phase or end-of-life phase of a product is multiplied by its corresponding weighting factor to reflect the GWP caused by delayed emissions during the assessment period.

This method is suitable for the majority of plant-derived fibers to calculate the effect of carbon storage.

3. Case Study

3.1. Carbon Storage Quantification of Hemp Textile Products

To demonstrate the carbon storage and the delayed emission effect of hemp fiber products, a hemp T-shirt, hemp slipcover, and hemp fiber handicraft were taken as the research objects. The manufacturing rate from fresh stem to products was assumed to be 30%, 45% and 60%, respectively. As shown in the blue part in Figure 1, the research boundary included the hemp cultivation phase, hemp product use phase, and the end-of-life phase.

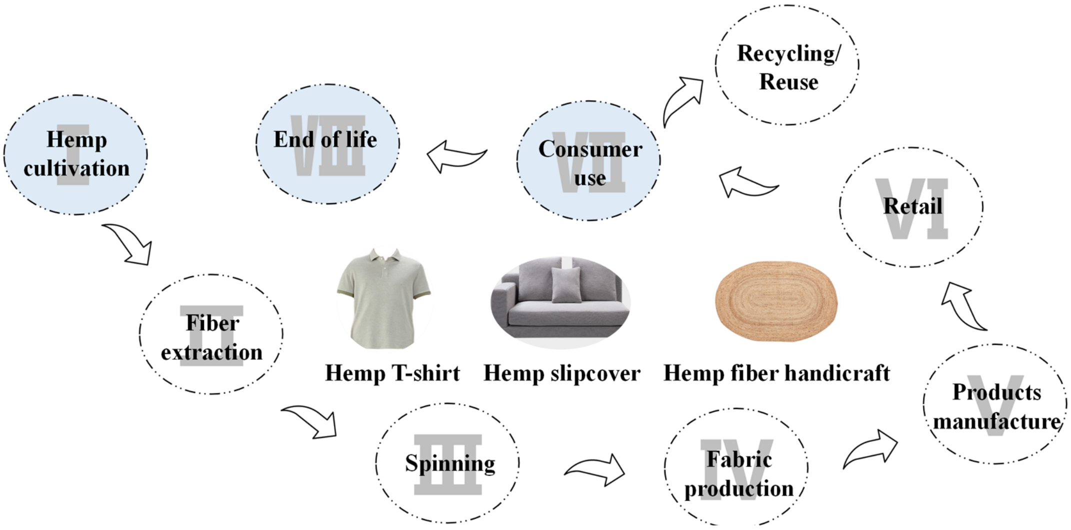

Figure 1. The total life cycle of hemp textile products.

To calculate the carbon storage of soil, the hemp farmland information is as follows: it is located in a temperate monsoon climate region, which is located in the China northeast, which has black soil and is cultivated for a long time, with sufficient cultivation and medium investment. The planting area is 10 mu, the fresh stem yield is 500 kg/per mu, and the growth period is 120 days. The factors required to calculate the soil carbon storage during the hemp cultivation period are shown in Table 2. According to Equations (1) and (2), the carbon storage per mu in the soil of hemp during the growth period of 120 days is 52.36 kg CO_2.

Table 2. Factors required for soil carbon sequestration.

Initial Year of Accounting Period				
SOC_{ref}	**F_{LU}**	**F_{MG}**	**F_I**	**A**
6333 (kg C/mu)	0.69	1.0	1.0	10 mu
Last year of accounting period				
SOC_{ref}	**F_{LU}**	**F_{MG}**	**F_I**	**A**
6333 (kg C/mu)	0.69	1.08	1.11	10 mu

Additionally, the carbon storage of three hemp textile products is determined by the biomass of plants. The detailed information of the products is shown in Table 3, and the results were calculated based on the average results from literature [28–31] and the formulas listed in the Methodology section. The carbon content of the hemp fibers contained in the hemp products was taken into account as CO_2 storage in accordance with PAS2050 [7]. As summarized in Table 2, the CO_2 storage of hemp T-shirt, hemp slipcover, and hemp handicraft are 0.3666 kg, 1.8333 kg, and 0.9165 kg, respectively. These results demonstrate that plant-derived fiber has a positive impact on climate change due to the storage of CO_2 in the soil and plant.

Table 3. Basic information and the carbon storage results of the three hemp products.

Product	Fiber Content (%)	Weight (kg Biomass)	CO_2 Storage of Products (kg CO_2)	Life Span (Year)	Effects of Delaying (%)
New hemp T-shirt	100	0.2	0.3666	5	3.83
New hemp slipcover	100	1.0	1.8333	25	19.68
New hemp fiber handicraft	100	0.5	0.9165	50	41.12

3.2. Carbon Storage Effect of Hemp Textiles

A 100-year horizon is now routinely selected as the reference time scale for calculating GWPs on account of the extensive use of 100-year GWPs in Kyoto Protocol-related policies and accounting. Therefore, this study restricted CO_2 storage estimations to the 100 years after the manufacturing of the product. The effectiveness of CO_2 storage depends on the lifespan of the product. When CO_2 emissions are delayed with the carbon storage time (in the examples of 5, 25, and 50 years), the shaded area will shift out of the 100-year time frame. As a result, the GWP of the hemp products will be postponed. The lifespan of a hemp T-shirt is 5 years, a hemp slipcover is 25 years, and a hemp fiber handicraft is 50 years. As shown in the shaded region in Figure 2, the delayed emission effects of the temporarily stored carbon in 3 hemp products are 3.83%, 19.68%, or 41.12%, respectively. It can be seen that the longer the emissions are delayed, the greater the carbon storage effect. Additionally, the delayed emission effects of the temporarily stored carbon are not related to the amount of carbon storage in the product. Only during the final release should the original carbon storage be considered.

The advantage of carbon storage in plant-derived fibers textile products in the baseline LCA, however, is not related to the delayed emissions, but is rather related to the end-of-life scenario. In the end-of-life phase, three baseline scenarios were assumed to analyze the impact of different waste disposal methods on carbon storage: (1) 100% incineration; (2) 100% landfill; (3) 60% incineration and 40% landfill. For the incineration scenario, the carbon stored in the product will be released into the atmosphere immediately after its useful life. Meanwhile, 1.3% of the carbon is released at a constant rate for 20 years after the end of its useful life, and 98.7% of the carbon is stored permanently in the following years. Figure 3 shows the change of the carbon storage content of a hemp T-shirt, hemp slipcover, hemp fiber handicraft for incineration and landfill scenarios within 100 years after product formation. The initial carbon storage amount of a hemp T-shirt, hemp slipcover, hemp fiber handicraft are 0.3666 kg CO_2, 1.8333 kg CO_2, and 0.9165 kg CO_2, respectively. As shown in Figure 3, the incineration scenario releases carbon faster compared to the landfill scenario. For example, for hemp T-shirt 100% combustion, the stored carbon content of 0.3666 kg was immediately released at the end of the fifth year of its service life. For hemp T-shirt 100% landfill, only 0.0048 kg CO_2 was released to the atmosphere at a constant rate for 20 years.

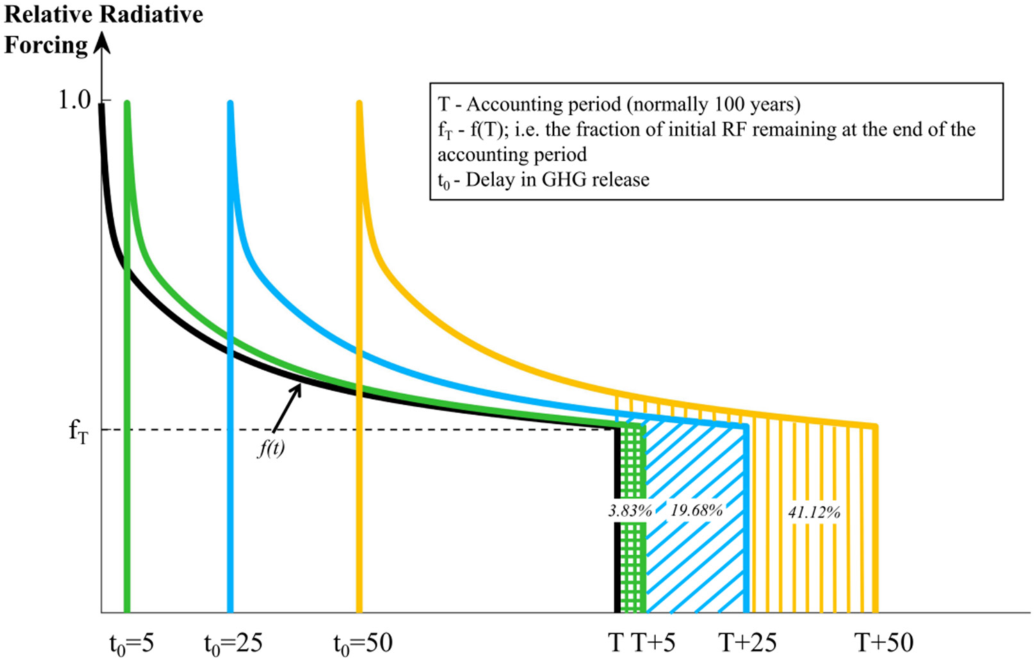

Figure 2. Delayed GHG release: concentration decay of different hemp products.

For the incineration scenario, the weighting factors were obtained for 1 kg of biogenic CO_2 emissions delayed by 5, 25, and 50 years, representing the impact of such delayed emissions (Table 4). In the case of the landfill, the weighting factors were calculated to represent the total impact of these delayed emissions, considering that 1 kg of biogenic CO_2 is emitted at a constant rate after the formation of the product. The impact of these emissions reflecting the timing of release is derived by multiplying these parameters by the CO_2 released in hemp products.

Table 4. The weighting factor and negative carbon emission of three hemp products based on three different types of disposal.

Product	Hemp T-Shirt			Hemp Slipcover			Hemp Fiber Handicraft		
	Incineration	**Landfill**	**Hybrid Scenario**	**Incineration**	**Landfill**	**Hybrid Scenario**	**Incineration**	**Landfill**	**Hybrid Scenario**
Weighting factor	0.96	0.85	/	0.81	0.64	/	0.62	0.42	/
Negative carbon emission (kg CO_2e/product)	0.701	0.715	0.707	1.718	2.058	1.854	0.743	1.084	0.879

Owing to the significantly varied service life and end-of-life time of hemp fiber products, the delayed emissions effect of CO_2 storage may be significant to the carbon footprint assessment of a product. Figure 4 shows the effect of CO_2 storage for three hemp products in three end-of-life scenarios. Large differences in the results can be observed in the various end-of-life scenarios. For biogenic carbon storage, the CO_2 storage effect of the scenario with incineration disposal is consistently lower than storage for the landfill and hybrid scenario. Furthermore, the CO_2 storage effect of a hemp T-shirt, hemp slipcover, and hemp handicraft in a landfill is higher than incineration: 3.98%, 82.8%, and 60%, respectively. The carbon storage effect gap between incineration and landfill is related to the original amount of carbon storage. It can be seen that the higher the amount of the original carbon storage, the more significant the carbon storage effect. The results indicate that the waste management of landfill for plant-derived fiber textile products may be preferable from carbon storage effect.

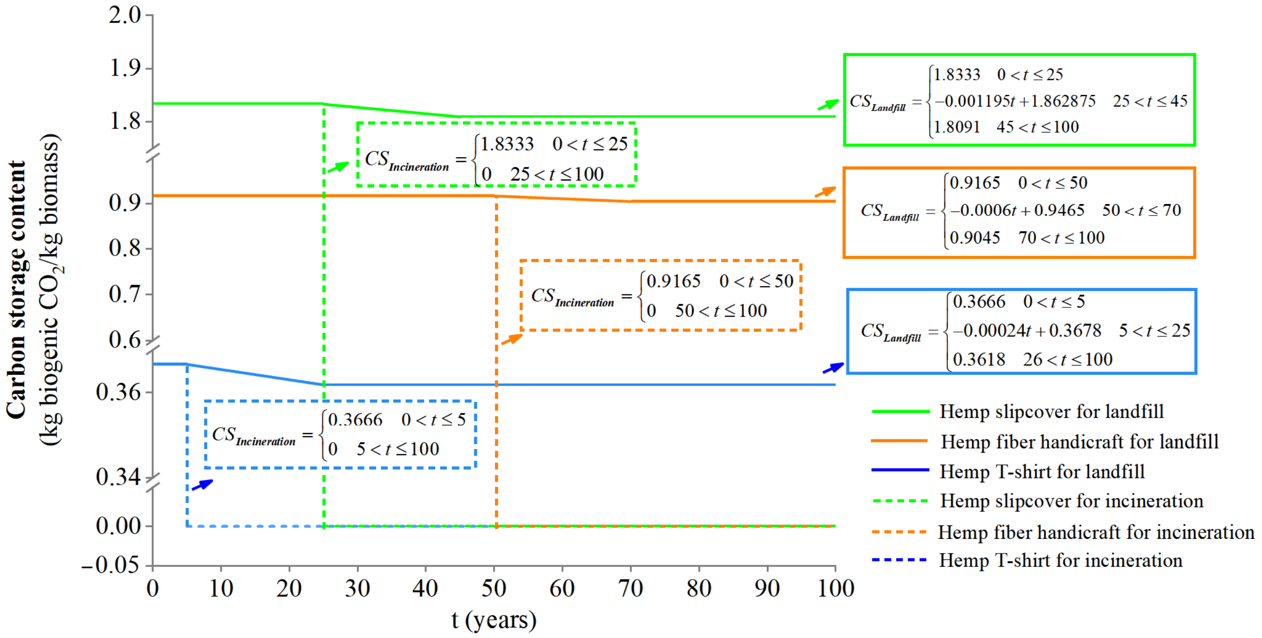

Figure 3. Carbon storage content of a hemp T-shirt, hemp slipcover, and hemp fiber handicraft within 100 years after the formation of the product.

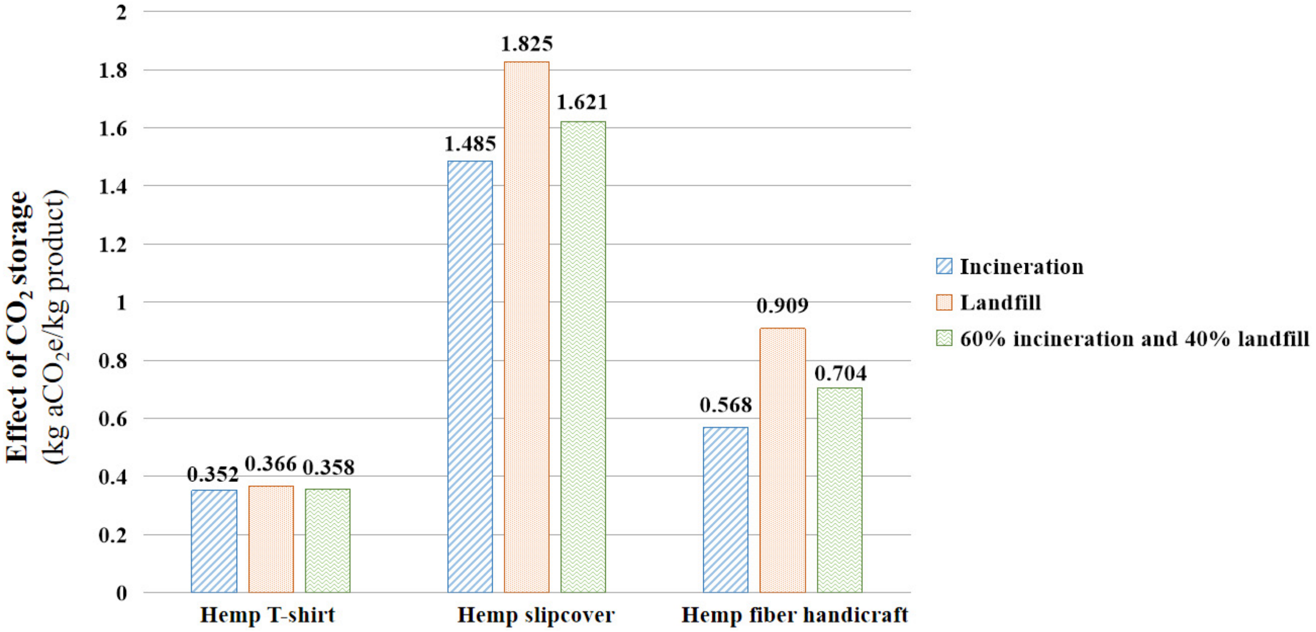

Figure 4. The effect of CO_2 storage for three hemp products.

Additionally, the carbon storage of soil and the effect of delaying the release of temporarily stored carbon can be considered as negative emissions in the carbon footprint assessment of hemp products. The combined manufacturing rates of three hemp products and the negative carbon emission from cradle to grave of three end-of-life scenarios were shown in Table 4. It is evident that the landfill scenario has higher negative carbon emissions than the incineration and hybrid scenarios. The negative carbon emission of hybrid scenario of 60% incineration and 40% landfill was in the middle of the other two scenarios.

3.3. Carbon Neutrality of Plant-Derived Fibers

Carbon storage analysis showed the potential to assess the carbon neutrality of textile products made from plant-derived fibers, allowing us to emphasize the hotspots of carbon emission reduction. The carbon storage of plants was the principal CO_2 reduction source, as demonstrated in our study. However, it should be noted that the service life of textile products made from plant-derived fibers may not be as long as we assumed. In order to further enhance the carbon storage effect associated with the product usage stage, consumers should be encouraged to extend the wear/use life or engage in recycling/reuse for lifespan extension. Additionally, promoting optimal care practices for textiles through publicity could also help achieve this goal. Additionally, considering the CO_2 storage in soil, the conversion of traditional cultivation to sustainable organic production may offer significant CO_2 storage opportunities, such as adopting sustainable input and management practices.

In this hypothetical situation, when calculating the life cycle carbon footprint of hemp textile products, the effect of products carbon storage period on the delayed emissions can be obtained. Interventions can be targeted from the production, consumption, and use stages to extend the life cycle of products, so as to partially offset the impact of carbon emissions and achieve real sustainable development. However, the effect of carbon storage was not recommended to offset carbon emissions caused by textile production in the current practice of carbon footprint assessment, owing to the biogenic CO_2 that will release into the atmosphere. As shown in Figure 5, Vogtländer et al. [32] presented a biogenic CO_2 cycle system to offset CO_2 emission—unless the plant products were burnt for electricity and/or heat, and the plants were replanted. In other words, biogenic CO_2 released at the end-of-life phase should be recaptured or reused; thereby the effect of carbon storage could be included in the life cycle carbon footprint assessment.

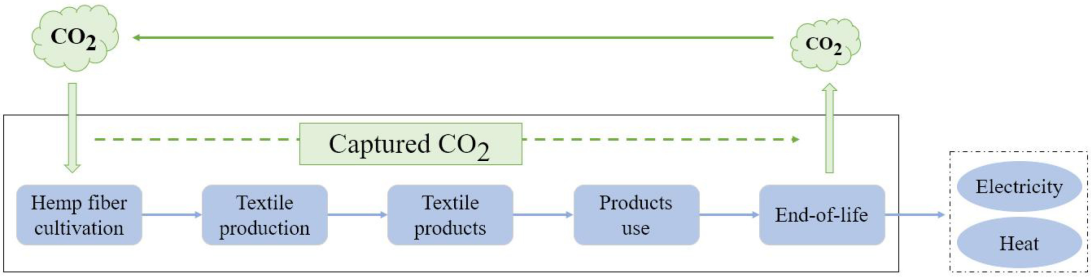

Figure 5. The entire life cycle of biogenic CO_2.

Moreover, obsolete products made from plant-derived fibers can be broken down into smaller units and converted into carpets, bags, accessories, wadding, and other recyclable items, thereby extending the service life of the product while reducing raw material consumption and CO_2 emissions. In addition, once the service life of products made from plant-derived fibers has expired, the energy recovery can be performed, which refers to the incineration process of the products. The energy recovery of products can provide advantageous energy generation [33]. The heat generated by combustion can be utilized to generate electricity, thereby reducing the usage of coal and, on the other hand, minimizing CO_2 emissions.

4. Conclusions

Carbon storage by fibrous plants plays an important role in the global carbon cycle. Since biogenic carbon was captured and stored in soil and plants from the atmosphere during plant-derived fiber plants growth, the radiative forcing is avoided, thereby having a positive impact on climate change. More emphasis on the CO_2 storage of plant-derived fibers and maximizing the carbon storage period will help reduce the total carbon emissions from the textile industry. To the best of our knowledge, this is innovative systematic research, as we apply a soil organic carbon method and dry weight biomass method to assess the carbon storage of plant-derived fiber textile products. Furthermore, a robust model was constructed in this study to adequately evaluate the carbon storage effect and the effect of the lifespan of a product on the temporary carbon storage effect. The results show that plant-derived fibers have a positive impact on climate change due to the storage of CO_2, in soil and plant, and that the carbon storage effect improves with the continued lifespan of the product. Furthermore, if there is a possibility that carbon storage may be released back into the atmosphere, the landfill option for hemp fiber products may be a more favorable disposal option from a carbon storage perspective. When biogenic CO_2 released at the end-of-life phase needs to be recaptured or reused, the negative carbon emission of soil and carbon storage effect can be included in carbon footprint assessment in the whole life cycle of plant-derived fibers and textile products, which reflects the carbon-neutralization property of plant-derived fibers. Considering the carbon footprint assessment of plant-derived textile materials, future studies should consider carbon storage effects from cradle to grave to comprehensively assess the environmental impacts.

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