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Field-based life cycle assessment of resource recycling and biochar strategies for sustainable gambiered silk dyeing

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Abstract

Traditional natural dyeing is increasingly promoted as a sustainable alternative to synthetic textile dyeing, yet its actual environmental performance remains poorly quantified. Gambiered silk dyeing, a heritage textile process in southern China, relies on large inputs of dye yam biomass and iron-rich river mud, highlighting the potential of converting dye yam residues into biochar for waste valorization and carbon sequestration. Here, a field-based life cycle assessment, life cycle costing, and carbon footprint analyses were integrated to evaluate the environmental hotspots and cleaner production potential of gambiered silk dyeing. For the current production system, the endpoint impact was 14.06 kPt, mainly driven by electricity use, transportation, and diesel consumption, whereas labor dominated the production cost. Recycling iron-rich river mud reduced the demand for fresh mud extraction and processing, decreasing the total environmental impact and carbon emissions by 28.9% and 30.7%, respectively. Further valorization of dye yam residues into biochar introduced additional processing-related impacts but provided an estimated carbon sequestration benefit of 173 t CO_2-eq, thereby shifting the system from net carbon emissions of 142.7 t CO_2-eq to a positive carbon budget of 6.0 t CO_2-eq. Biochar valorization also improved economic performance by offsetting part of the production cost. Overall, these findings highlight the potential of converting dye yam residues into value-added biochar, alongside river mud recycling, to enhance resource efficiency, reduce carbon emissions, and support the sustainable development of traditional textile production.

Highlights

- Field-based LCA, LCC, and carbon footprint analysis were integrated for gambiered silk dyeing.
- Electricity, transportation, and diesel use were key environmental hotspots.
- Recycling river mud reduced total environmental impacts and carbon emissions.
- Dye yam residue-derived biochar enabled a positive carbon budget and economic benefit.

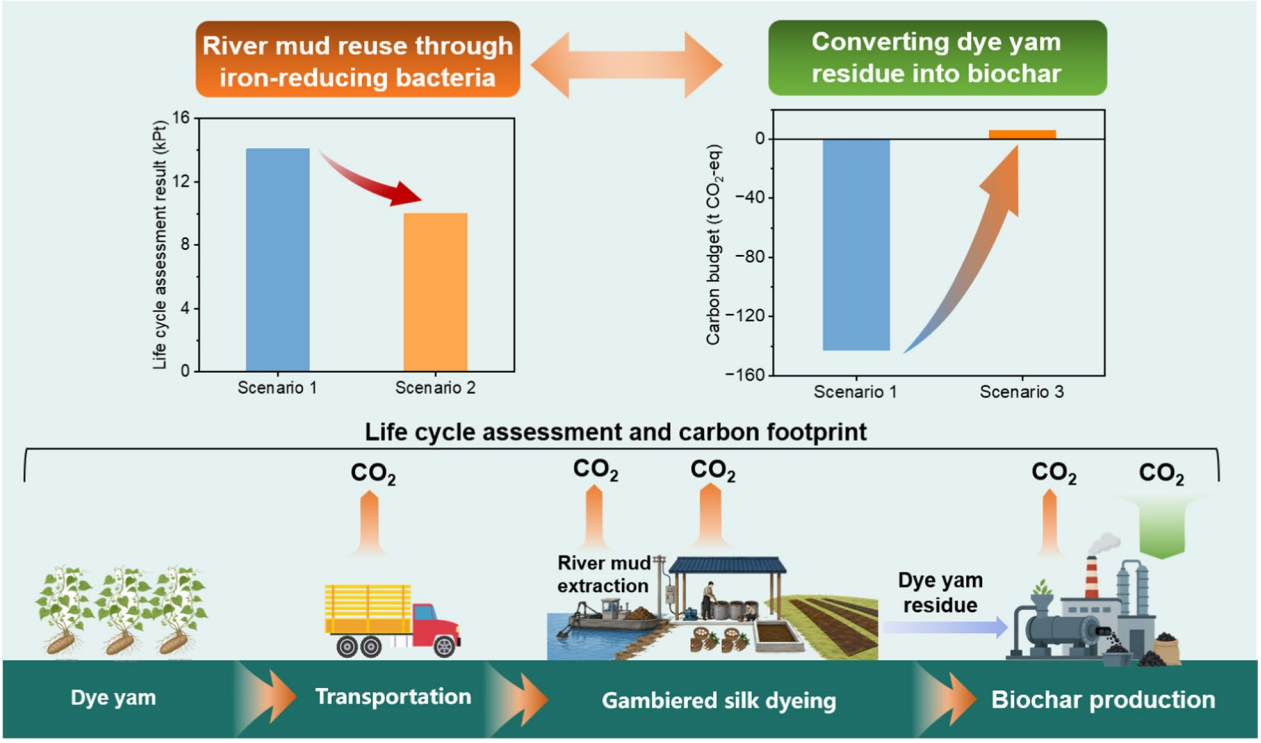
Keywords Natural dyeing, Biochar, Life cycle assessment, Carbon emission reduction, Sustainable production

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Graphical Abstract



1 Introduction

Natural dyes derived from renewable bio-based resources have long been used in textile production and are generally considered more environmentally friendly than synthetic dyes due to their lower reliance on synthetic chemicals (Fazal ur et al. 2022; Vankar 2017). In recent years, traditional dyeing processes using natural dyes have attracted renewed attention, driven by growing interest in traditional craftsmanship and cultural heritage, which has in turn increased global demand for natural dye products (Surjit et al. 2023). This trend is particularly evident in southern China, where abundant plant dye resources and well-established textile manufacturing clusters have supported the commercialization of natural dyeing practices (Li et al. 2022). Gambiered silk, also known as *xiangyunsha*, is a representative natural-dye-based heritage textile originating from southern China, produced through a distinctive dyeing process that combines plant-derived dyes with iron-rich river mud (Yang et al. 2018). Since the *Xiangyunsha* dyeing and finishing technique was inscribed on China's second batch of national intangible cultural heritage list in 2008, growing demand for traditional cultural products has contributed to the expansion of the gambiered silk industry (Zhou et al. 2024), particularly in Guangdong and Guangxi provinces. China's annual production of gambiered silk is estimated at approximately 50 million meters.

The traditional production process of gambiered silk is well established and consists of several key steps, including plant dye extraction, repeated dyeing and sun-drying, and treatment with iron-rich river mud (Pan et al. 2018; Wen et al. 2024). Although natural-dye-based processes generally require fewer synthetic chemical inputs, gambiered silk production still consumes substantial amounts of biomass feedstocks, water, electricity, and river mud, raising concerns about its environmental impacts and sustainability. These impacts are primarily associated with two processes. First, gambiered silk dyeing requires large quantities of dye yam for pigment extraction (Lin et al. 2024). However, the aqueous pigment extraction yield is only 13.53% (Zhong et al. 2019), generating substantial amounts of dye yam residues after extraction. Second, the traditional mud-coating process requires substantial quantities of river mud sourced from waterways in China's Pearl River Delta, partly due to its relatively low content of HCl-extractable Fe(II) (0.68–1.43 mg g^{-1}) available for mud dyeing (Pan et al. 2017a).

River mud extraction may disturb riverine ecosystems, and its excavation, transportation, and filtration consume diesel and electricity, contributing to greenhouse gas emissions. Moreover, China has been advancing its "dual carbon" strategy of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060 (Jia et al. 2022), as outlined in the Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality and the Action Plan for Carbon Dioxide Peaking Before 2030 issued in 2021. Accordingly, increasing attention has been paid to the carbon emissions associated with gambiered silk production and their implications for national low-carbon development goals (Chen and Lin 2021). Addressing these environmental and policy challenges requires a systematic assessment of the production process. However, a comprehensive evaluation of the environmental impacts and carbon footprint of gambiered silk production remains lacking.

Life cycle assessment (LCA) is a well-established and standardized approach for quantifying the environmental impacts and carbon footprint of production systems (Klöpffer and Grahl 2014; Matuštík et al. 2020). It has been widely used to evaluate the environmental impacts of a variety of conventional industries, including textile dyeing (Hammar et al. 2023), reconstituted bamboo material production (Chen et al. 2025), and traditional sake brewing (Seo et al. 2025). For example, LCA-based evaluations of the *Rubia tinctorum* L. dyeing process have shown that ultrasound-assisted dye extraction reduces solvent and energy consumption, thereby lowering environmental impacts and carbon emissions (Agnhage et al. 2017). Beyond evaluating environmental impacts, LCA can further identify key environmental hotspots and reveal trade-offs across multiple impact categories, thereby supporting targeted improvements in production processes. In flax technical textile production, LCA identified agricultural activities and electricity production as the main contributors to the overall environmental impacts (Gomez-Campos et al. 2021). Therefore, LCA provides a suitable framework for evaluating the environmental impacts and carbon footprint of traditional gambiered silk production and identifying key environmental hotspots across its production process.

In addition, the large amounts of dye yam residues generated during pigment extraction in gambiered silk production require effective treatment. Converting these residues into biochar offers a promising pathway, as biochar has diverse environmental applications (He et al. 2022), including the remediation of contaminated water and soils and the improvement of soil fertility (Chen et al. 2019; Qiu et al. 2022). Moreover, owing to its relatively stable carbon-rich structure, biochar can contribute to long-term carbon sequestration (Smith 2016). Previous studies have shown that approximately 90% of the carbon in biochar can remain in soil after 40 years, highlighting its potential for stable long-term carbon storage (Liu et al. 2022b). At the global scale, assessments have suggested that biochar systems could deliver emission reductions of 3.4–6.3 Pg CO_2-eq, approximately half of which would be achieved through carbon dioxide removal (Lehmann et al. 2021). Although biochar carbon stability and sequestration potential depend on feedstock properties, pyrolysis conditions, and stability assessment methods (Ippolito et al. 2020), these studies provide a general basis for evaluating the long-term carbon storage potential of biochar. Given the technical maturity of biochar production, the conversion of agricultural residues, sludge, and other organic wastes into biochar has been increasingly explored worldwide (Wang and Wang 2019). Therefore, converting dye yam residues into biochar may provide a feasible strategy for reducing waste disposal pressure, enhancing carbon sequestration, and improving the overall sustainability of gambiered silk production.

Herein, this study aims to evaluate the environmental and economic sustainability of gambiered silk production through life cycle assessment and life cycle costing. Specifically, the objectives are to: (1) quantify the environmental impacts and carbon emissions of gambiered silk production using data from a representative dyeing facility and identify the key contributing processes; (2) evaluate the environmental benefits of optimizing iron-rich river mud utilization and converting dye yam residues into biochar, with a focus on waste valorization and carbon sequestration; and (3) assess the life cycle costs of gambiered silk production under different scenarios to evaluate their economic feasibility. The findings of this study support the green and sustainable development of traditional gambiered silk production.

2 Materials and methods

2.1 Case description and system boundaries

The study site was a gambiered silk dyeing factory that has been operating for several decades in Shunde District, Foshan City, in the Pearl River Delta region of southern China. According to information provided by the gambiered silk dyeing factory, renewed market demand since 2020 has driven the rapid expansion of the sector. However, the rapid expansion of this industry has increased resource use, energy consumption, and carbon emissions, raising growing concerns among local residents and government authorities about its potential environmental impacts. These concerns also highlight the need for targeted process improvements to align gambiered silk production with green and sustainable development goals. To systematically evaluate environmental impacts and identify improvement opportunities, the existing

gambiered silk dyeing process was first defined as the reference scenario, namely Scenario 1. Building on this reference assessment, two improved conceptual factory scenarios were then developed to address two key issues in the current production process: the reuse of iron-rich river mud and the conversion of discarded dye yam residues into biochar. These scenarios were designed to evaluate the potential of targeted interventions to enhance resource recycling and reduce environmental impacts.

Scenario 1 (S1) represents the current gambiered silk dyeing process. As shown in Figs. 1 and S1, the process starts with the preparation of the dye bath using dye yam (*Dioscorea cirrhosa* Lour.), a climbing vine native to southern China and parts of Southeast Asia. Its spherical tubers, which contain 11–31% tannins, produce a natural red-brown dye with antibacterial and insect-repelling properties. Dye yam tubers are manually harvested in the mountainous areas of Fangchenggang, Guangxi Province, and transported approximately 600 km by road to dyeing facilities in Shunde District, Foshan, Guangdong Province. Upon arrival, the dye yams are washed to remove surface impurities, mechanically ground to break down plant tissue, and then mixed with water to extract the pigment-rich solution. The resulting extract is subsequently diluted with water in dyeing vats before being used for fabric dyeing. Pre-scoured silk is then immersed in the dye liquor and manually handled to improve tannin absorption. After saturation, the fabric is spread flat on grassy surfaces for solar irradiation, facilitating oxidative condensation of catechin-based tannins. The dyeing and sunning cycle is repeated manually 14–28 times, depending on the type of gambiered silk targeted. This iterative process gradually develops the characteristic reddish-brown hue and establishes a tannin-rich substrate necessary for the subsequent iron-mediated mordanting process. In addition, large amounts of dye yam residues are generated and transferred to downstream enterprises, mainly for combustion or composting, which are outside the system boundary of S1.

Following repeated dyeing and sunning cycles, the fabric undergoes a mud-coating process, a defining stage in gambiered silk production. Iron-rich river mud functions as a natural mordant, providing ferrous and ferric ions that react with the tannins adsorbed onto the silk surface to generate stable iron-tannin complexes. These complexes contribute to the characteristic dark coloration and metallic sheen of gambiered silk, while also imparting excellent textile properties, including hygroscopicity, UV protection, and antibacterial and antioxidant activities. Specifically, river mud is collected by dredging vessels from river bottoms at depths greater than 5 m, and harvesting sites are typically left fallow for 2–3 years before reuse. The collected mud is transported to the facility, where it is repeatedly filtered to



Fig. 1 Gambiered silk dyeing processes

achieve a fine, paste-like consistency suitable for coating. The mud is then applied manually and mechanically to the fabric, which is laid face-down on sandy ground for approximately one hour before washing. After cleaning, the textile is sun-dried and treated once more with dye yam extract to enhance color fixation. Once drying is complete, the textile is inspected, measured, rolled, and packed.

Scenario 2 (S2) introduces an internal reuse strategy for iron-rich river mud within the current production system (Fig. S2). In conventional practice, river mud is used only once during mordanting and then discarded, despite retaining a substantial amount of iron. Previous studies showed that reactive ferrous iron in river mud collected from the Pearl River accounts for only 5–10% of total iron (Pan et al. 2017b), indicating that most Fe remains unused during the dyeing process and that river mud has substantial potential for resource recovery and reuse. However, reuse is limited by the gradual depletion of active ferrous iron, which reduces mordanting effectiveness over repeated cycles. To address this limitation, microbial iron reduction was introduced as an effective strategy to regenerate active ferrous iron in river mud. Previous studies have demonstrated that bioaugmentation with iron-reducing bacteria, such as *Shewanella decolorationis* S12, can enhance the microbial reduction of Fe(III) to Fe(II) in river sediments, thereby restoring their dyeing performance (Pan et al. 2019). Specifically, *Shewanella decolorationis* S12 was assumed to be cultured in LB medium at 30 °C for 8 h, after which the culture was adjusted to OD600 = 1.0 and inoculated into river mud at 3 mL per 3 g, followed by incubation at 30 °C in the dark for 7 days (Pan et al. 2017b). This approach provides a feasible strategy for regenerating river mud and improving its reuse efficiency, potentially reducing the regeneration period to several days.

Based on this analysis, Scenario 2 was proposed to evaluate a river mud reuse strategy for reducing fresh mud extraction and improving resource recycling. Specifically, the river mud suspension after dyeing is first transferred to on-site sedimentation ponds, where the solid mud fraction is allowed to settle. After sedimentation, the clarified supernatant is discharged, and the settled mud slurry is then transferred to a reduction tank amended with iron-reducing bacteria. Through microbial treatment, active ferrous iron is generated, allowing the mud to be recirculated into subsequent mud-coating cycles. By enabling the recovery and reuse of residual iron in river mud, this closed-loop approach reduces the need for river mud extraction, thereby lowering resource consumption, energy use, and related environmental impacts. All other production processes remain identical to those described in Scenario 1.

Scenario 3 (S3) builds on iron-rich river mud reuse by further incorporating the conversion of dye yam residues into biochar (Fig. 2). The processing of dye yam, a key raw material in gambiered silk production, generates large amounts of residues after pigment extraction. As identified in Scenario 1, these dye yam residues are primarily treated through composting or direct combustion as fuel. Recent studies suggest that converting biomass residues into biochar represents an emerging and scalable pathway for sustainable waste valorisation (He et al. 2022). Biochar production is technically mature and mainly relies on high-temperature pyrolysis under oxygen-limited conditions, producing a carbon-rich material with high value and broad applications (Wang and Wang 2019). It contributes to climate change mitigation through stable carbon sequestration and serves as a multifunctional material for soil remediation and water purification. In Scenario 3, as shown in Fig. 2, dye yam residues are transported to a biochar production facility. The biochar production process mainly consists of biomass drying and pyrolysis.

The system boundary encompasses the major processes involved in gambiered silk production. For Scenario 1, the system boundary included dye yam transportation, dye extraction, fabric dyeing, river mud extraction, and mud coating (Fig. S1). Scenario 2 incorporated additional processes associated with microbial reactivation and repeated reuse of river mud (Fig. S2), thereby reducing the demand for fresh river mud. For Scenario 3, biochar production from discarded dye yam residues was further included (Fig. S3). Across these processes, material inputs, electricity and diesel consumption, resource use, and carbon inputs and outputs were systematically quantified.

2.2 Life cycle assessment

2.2.1 Goal, scope, and functional unit

Life cycle assessment (LCA) has been widely used to evaluate the environmental impacts of industrial production (Klöpffer and Grahl 2014). In this study, the LCA was conducted in accordance with ISO 14040 and ISO 14044 (Finkbeiner et al. 2006). The goal of the present study was to evaluate the environmental impacts of gambiered silk production under Scenarios 1, 2, and 3. The study also identified the contributions of different production processes. The scope of this LCA was limited to the production stage of gambiered silk, excluding the use and end-of-life stages, as illustrated in the system boundary diagrams (Figs. 2, S1, and S2). The functional unit was defined as 350,000 m of gambiered silk, corresponding to the annual production output of the representative dyeing facility investigated in this study. This functional unit provides a consistent basis for comparing

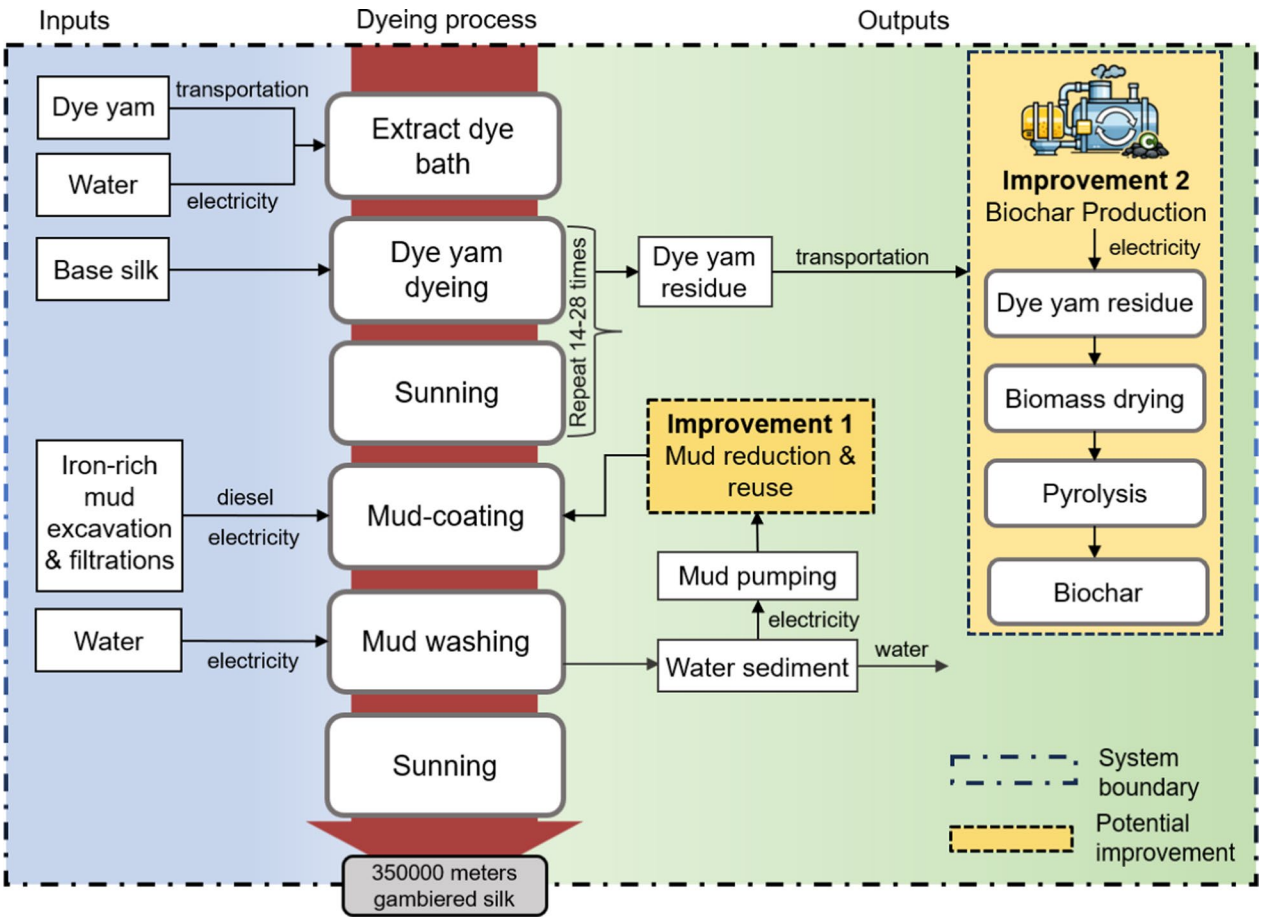


Fig. 2 LCA system boundaries of the improved gambiered silk dyeing process integrating iron-rich river mud reuse and converting dye yam residues into biochar production

the environmental impacts and life cycle costs across different scenarios.

2.2.2 Life cycle inventory

The life cycle inventory data cover all stages of the dyeing process following LCA guidance (Bjørn et al. 2018; Saavedra-Rubio et al. 2022), including raw materials, transportation distances, energy, electricity, and emissions. For Scenario 1, as shown in Table 1, detailed life cycle inventory data for gambiered silk production were collected through on-site investigations at a representative dyeing facility from October 2023 to March 2025. To ensure data reliability, key production parameters were verified through consultations with factory technical personnel, and the collected data were reviewed for completeness and consistency. The specific inventory includes dye yam (*Dioscorea cirrhosa* Lour.), river mud, electricity, water, diesel, and transportation. For river mud reuse in S2, the theoretical number of reuse cycles was estimated based on the reactive Fe(II) content in river mud and the measured iron loading in the finished gambiered silk fabric (319.4 mg m^{-2}, based on factory data). Assuming complete utilization of the potentially available iron through repeated microbial reactivation, each batch of river mud was estimated to support approximately 14 reuse cycles. The detailed calculation procedure is provided in the Supplementary Information (Text S1). To account for the uncertainty associated with this idealized assumption, a sensitivity analysis was conducted by considering 1, 4, 8, and 14 reuse cycles. River mud reuse also reduced diesel and electricity consumption associated with mud extraction and processing. In Scenario 3, dye yam residues are converted into biochar, and the corresponding inventory data were obtained from the literature (Liu et al. 2022b). Producing 1 tonne of biochar requires approximately 3.3 tonnes of biomass and 12 kWh of electricity, with associated emissions of CO_2, CO, NO_x, and SO_2. Detailed data sources for each scenario are provided in Table 1.

2.2.3 Life cycle impact assessment

Life cycle impact assessment (LCIA) was conducted using the ReCiPe method, which is among the most

Table 1 Summary of LCA inventory data

Category	Sub-category	S1	S2	S3	Unit	Source
Gambiered silk dyeing	*Dioscorea cirrhosa* Lour	650	650	650	t	Manufacturer
	River mud	235.62	16.83	16.83	t	
	Electricity	100000	68953.12	68953.12	kWh	
	Water	3750	2003.61	2003.61	m^3	
	Diesel	4036.67	276.85	276.85	kg	
	Transportation	600	600	600	km	
Biochar production process (consumption inventory per tonne of biochar)	Biomass	/	/	3.3	t	Literature (Liu et al. 2022b)
	Electricity	/	/	12	kWh	
	CO_2 emission	/	/	1144	kg	
	CO emission	/	/	264	kg	
	NOx emission	/	/	43.56	kg	
	SO_2 emission	/	/	18.58	kg	

widely applied environmental impact assessment frameworks in LCA studies (Goedkoop et al. 2009; Huijbregts et al. 2017). The ReCiPe method includes midpoint and endpoint indicators and was implemented using SimaPro 9.5 software (Liu et al. 2022a). At the midpoint level, ReCiPe quantifies environmental impacts along the cause–effect pathway, providing detailed results for individual impact categories. In contrast, the endpoint level aggregates these impacts into three aspects: human health, ecosystems, and resources. The endpoint results are then further normalized and weighted into a single score. Therefore, both midpoint and endpoint approaches were employed to enable a more comprehensive evaluation of the three scenarios.

2.3 Life cycle cost analysis

A life cycle cost analysis was performed to characterize the cost composition of gambiered silk production and quantify the contributions of major cost categories. The cost structure of the gambiered silk dyeing process was categorized into labor, raw materials, and resource consumption, as summarized in Table S1. All costs were normalized to 350,000 m of gambiered silk produced annually. The cost data were collected from the gambiered silk production factory through on-site field investigations. In Scenario 2, the reuse of river mud reduces the need for river mud extraction and electricity consumption, thereby decreasing associated costs. In Scenario 3, beyond the cost savings associated with river mud recycling, the conversion of dye yam residues into biochar provides a value-added pathway for waste biomass utilization. Given the reported market value of biochar of approximately 295 USD per tonne, its production could generate additional economic value (You and Wang 2019), thereby further reducing overall production costs.

2.4 Carbon footprint

The carbon footprints of S1 and S2 were calculated based on the climate change impact results obtained from the LCIA, with greenhouse gas emissions primarily associated with electricity consumption, transportation, and diesel consumption. In S2, repeated river mud reuse reduced the demand for fresh river mud and associated diesel consumption, thereby lowering the overall carbon footprint compared with S1. For S3, net carbon sequestration was calculated by subtracting the total greenhouse gas emissions quantified through LCIA, including those associated with gambiered silk production and biochar production, from the carbon stored in dye yam residue-derived biochar (Liu et al. 2022a). Detailed calculation methods are provided in Supplementary Text S2.

3 Results and discussion

3.1 Environmental sustainability of resource recycling and biochar strategies

The overall environmental impacts of gambiered silk dyeing were evaluated using the ReCiPe endpoint method, which integrates normalized and weighted damage indicators into a dimensionless single score expressed in Points (Pt), with 1 kPt equivalent to 1000 Pt. As shown in Fig. 3a, the total environmental impact of the current gambiered silk dyeing production system (S1) was 14.06 kPt for an annual production output of 350,000 m, corresponding to 0.0402 Pt per meter of gambiered silk produced. After the reuse of iron-rich river mud, the environmental impact of S2 decreased by 28.9%. These results suggest that the reuse of iron-rich river mud can improve the environmental sustainability of the gambiered silk dyeing production process. When waste dye yam residues were further converted into biochar, the environmental impacts of S3 increased to 16.7 kPt

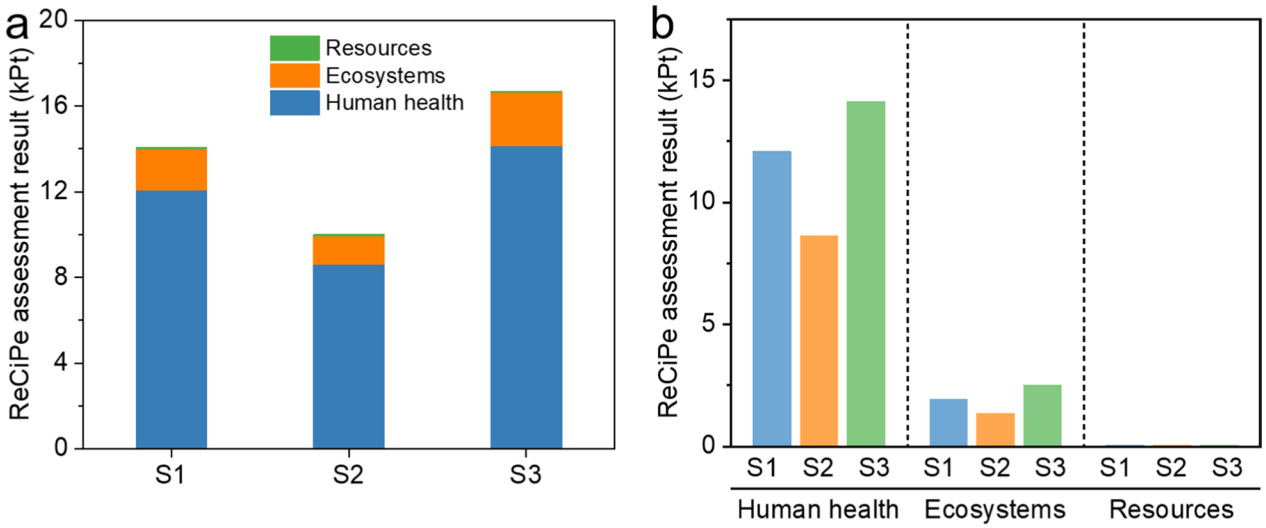


Fig. 3 LCA result by endpoint for each scenario (**a**), and the score of human health, ecosystems, and resources (**b**)

(Fig. 3a), indicating that the biochar production process introduced additional environmental impact. These impacts were mainly associated with electricity consumption and the resulting carbon emissions during biochar production (Roberts et al. 2010). According to the LCA framework, endpoint results are classified into three aspects: human health, ecosystems, and resources (Huijbregts et al. 2017). Across all scenarios, human health contributed most to the total environmental impacts, accounting for 84.6–86.0%, indicating that this category largely determined the overall LCA results. Among the three scenarios, S3 showed the highest impact on human health, followed by S1 and S2 (Fig. 3b). Ecosystems represented the second largest contributor to the total environmental impacts, and their impacts followed the same order across scenarios: S3 (2.5 kPt) > S1(1.9 kPt) > S2 (1.3 kPt). Compared with human health and ecosystems, the contribution of resources was negligible. Overall, the reuse of iron-rich river mud reduced impacts on human health and ecosystems, thereby lowering the overall environmental impact, whereas converting dye yam residues into biochar increased the overall environmental impact due to the additional energy and resource consumption associated with biochar production.

A midpoint LCIA was further conducted to provide a more detailed assessment of environmental impacts across specific impact categories. The midpoint results and the relative comparison are presented in Table S2 and Fig. 4. The results clearly showed that all impact categories in S2 were lower than those in S1. Notably, compared with S1, S2 reduced carbon emissions from 142773.33 to 98846.17 kg CO_2-eq, corresponding to a 30.7% decrease. This substantial reduction suggests that the process optimization in S2 effectively lowered the global warming potential of gambiered silk dyeing production. Furthermore, compared with S1, S2 showed substantial reductions in ozone formation, fine particulate matter formation, human carcinogenic toxicity, and terrestrial acidification, indicating lower human health- and ecosystem-related impacts. These reductions explain the lower endpoint impacts of S2 relative to S1 in the human health and ecosystems categories. After adding the biochar production process, carbon emissions further increased to 167006.34 kg CO_2-eq (Table S2), representing increases of 14.5% and 40.0% compared with S1 and S2 (Fig. 4), respectively. Although S3 increased carbon emissions, the resulting biochar partially offsets these emissions through carbon sequestration, as further evaluated in the following section. Moreover, compared with S1, the increased environmental impacts in S3 were mainly attributed to higher contributions from ozone formation, fine particulate matter formation, and terrestrial acidification, with increases ranging from 65.4% to 74.6% (Fig. 4). Therefore, iron-rich river mud reuse effectively reduces environmental impacts, whereas its integration with the conversion of dye yam residues into biochar slightly increases the overall environmental impact.

3.2 Contribution analysis and identification of key environmental hotspots

Based on the overall LCA results, a contribution analysis was further conducted to identify the key production processes responsible for the environmental impacts of gambiered silk production. In S1, electricity consumption was the dominant contributor, with an impact score of 8.82 kPt (Fig. S3), accounting for 63.0% of the total

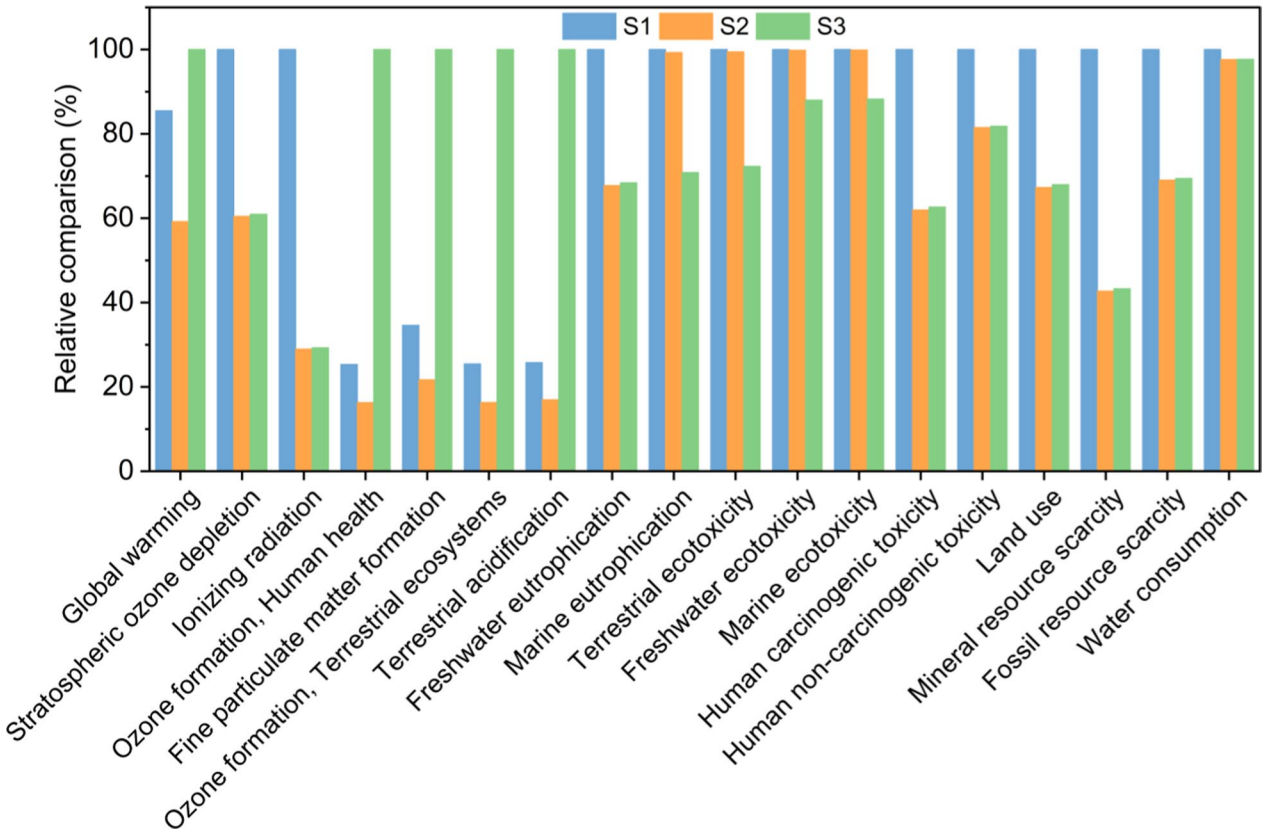


Fig. 4 Relative comparison results of LCIA (midpoint) for different scenarios

impact. This was followed by transportation and diesel consumption, which contributed 26.9% and 10.1%, respectively (Fig. 5a). The high contribution of electricity consumption was primarily associated with machinery used for dye yam juice extraction, river mud washing, and mud coating, which are essential steps in traditional gambiered silk production. Therefore, improving the energy efficiency of key production equipment should be prioritized to further mitigate the environmental impacts of gambiered silk production. Transportation-related impacts were primarily associated with the long-distance sourcing of dye yam from Guangxi Province, whereas diesel consumption was mainly linked to river mud extraction, reflecting the upstream energy demand for raw material acquisition. After the reuse of iron-rich river mud in S2, electricity remained the largest contributor, accounting for 61.2% of the total impact with an impact score of 6.1 kPt (Figs. 5b and S4). Transportation

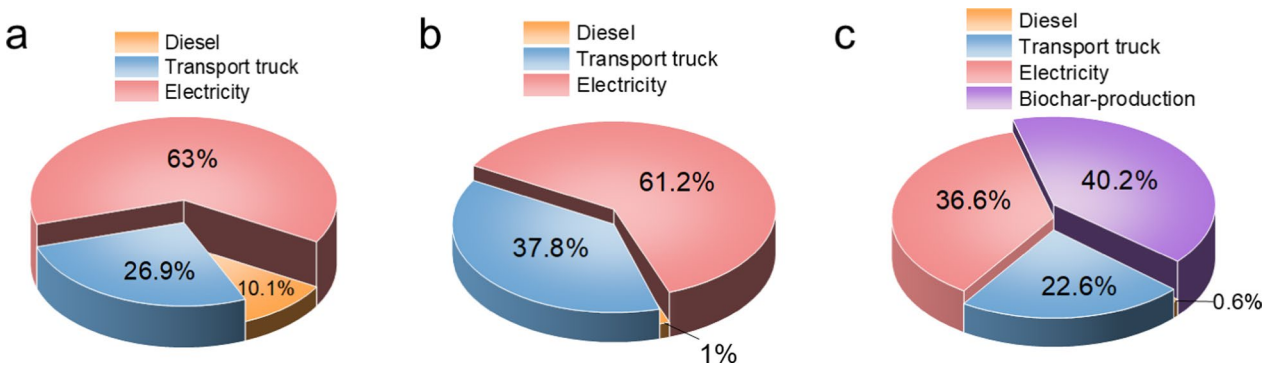


Fig. 5 Contribution of different production processes to the environmental impacts of S1 (**a**), S2 (**b**), and S3 (**c**)

contributed 3.77 kPt, accounting for 37.8%, whereas diesel consumption decreased to approximately 1.0% (Figs. 5b and S4). This indicates that river mud reuse effectively reduced diesel-related impacts from repeated mud extraction, although electricity use and transport still dominated the overall environmental impact. As a fossil-based and non-renewable energy source (Vieira and Huijbregts 2018), diesel generates considerable life-cycle carbon emissions from extraction to combustion. Therefore, reducing diesel use can further support the sustainable production of gambiered silk.

For S3, the introduction of biochar production further changed the process contribution structure. Biochar production became the largest contributor, accounting for 40.2%, followed by electricity use at 36.6% and transportation at 22.6%, whereas diesel consumption made only a negligible contribution (Fig. 5c). This result indicates that the conversion of dye yam residues into biochar introduced additional process-related environmental impacts, mainly due to energy inputs and emissions during biochar production (Liu et al. 2022a). Consequently, the environmental impact profile shifted from being dominated by electricity use in S1 and S2 to being jointly controlled by biochar production and electricity use in S3. Overall, these findings indicate that river mud reuse can reduce upstream diesel-related environmental impacts, whereas biochar production provides a promising pathway for dye yam residue valorization, although it also becomes a major contributor to environmental impacts in S3.

3.3 Carbon footprint

A carbon footprint analysis was further conducted to evaluate carbon emissions and sequestration potential across the three scenarios. As shown in Figs. 6a and S5, S1 generated approximately 142.7 t CO_2-eq of total carbon emissions, mainly from electricity consumption (95.8 t CO_2-eq), transportation (31.7 t CO_2-eq), and diesel use (15.3 t CO_2-eq). After improving the reuse of iron-rich river mud in S2, carbon emissions decreased to 98.8 t CO_2-eq (Fig. 6b), representing a reduction of 30.7% compared with S1. This reduction was mainly attributed to the decreased demand for repeated river mud extraction and processing. The improved process involved recycling spent river mud into on-site sedimentation ponds, followed by the addition of iron-reducing

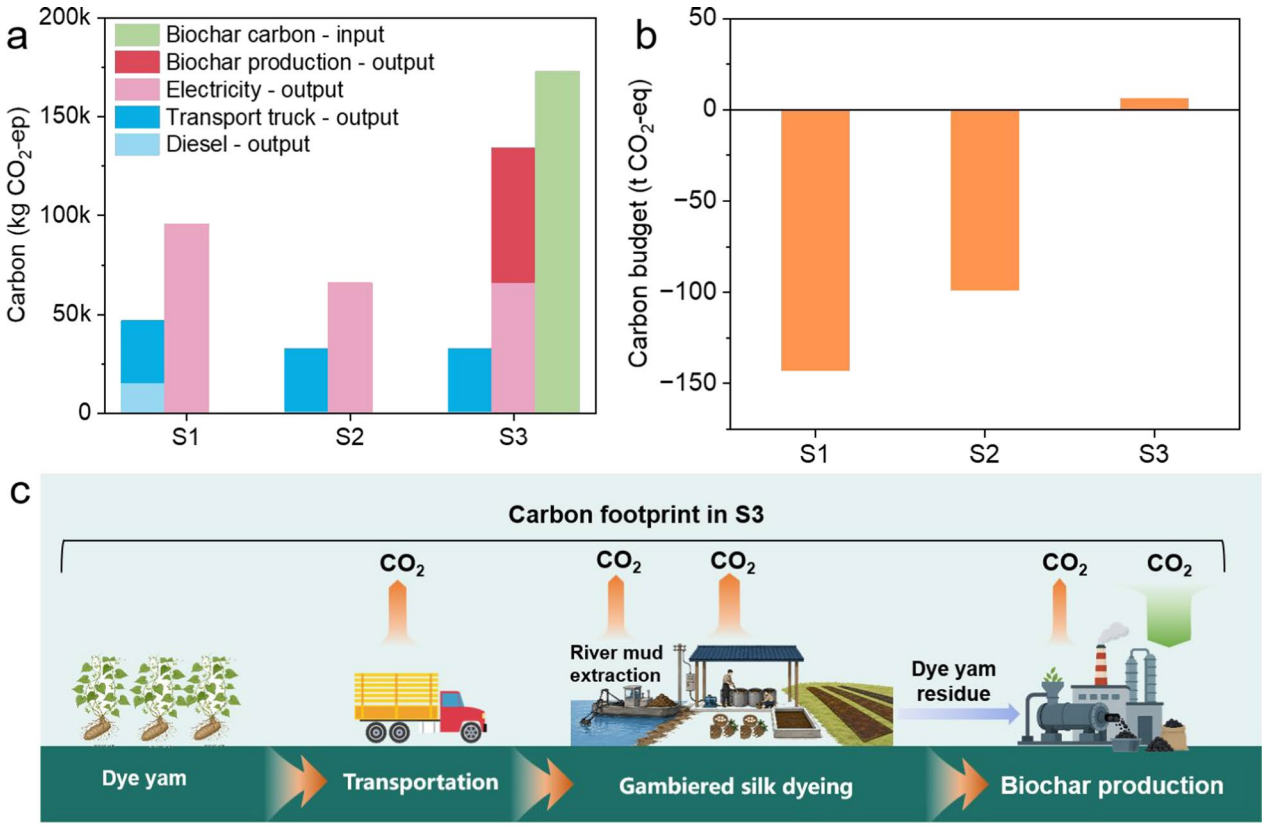


Fig. 6 The input and output of carbon in different scenarios (**a**), the carbon budget of different scenarios (**b**), the conception of carbon footprint in S3 (**c**)

bacterial inoculants to regenerate the Fe-rich mud. Because this process mainly relies on manual operation rather than energy-intensive excavation and mechanical processing, diesel- and electricity-related carbon emissions were reduced by 92.8% and 31.0% (Figs. 6a and S6), respectively. These results indicate that river mud recycling mainly reduced carbon emissions from the river mud extraction stage, particularly by lowering diesel consumption associated with repeated mud harvesting. Nevertheless, electricity consumption remained an important emission source in both S1 and S2, suggesting that further carbon emission reductions should focus not only on material recycling but also on improving energy efficiency and decreasing transportation distance.

In S3, the introduction of biochar production increased carbon emissions by 68.2 t CO_2-eq compared with S2 (Fig. 6a), mainly due to electricity input and direct emissions associated with the thermochemical conversion process (Matuštík et al. 2020). However, the produced biochar provided a substantial carbon sequestration benefit of 173 t CO_2-eq (Fig. 6a), which more than offset the production-related carbon emissions. Consequently, S1 and S2 remained net carbon-emitting systems, with carbon budgets of −142.7 and −98.8 t CO_2-eq, respectively, representing a 30.7% reduction in carbon emissions under S2. More importantly, S3 reversed the net carbon balance from −142.7 t CO_2-eq in S1 to +6.0 t CO_2-eq through biochar carbon sequestration (Fig. 6b). These quantified improvements highlight the potential of the proposed strategies to contribute to China's "dual carbon" goals and the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action), thereby supporting the low-carbon transition of traditional industries (Carlsen and Bruggemann 2022). This result indicates that converting dye yam residues into biochar is not only a high-value residue valorization strategy but also a pathway for transforming waste biomass into a stable carbon storage product. By integrating river mud recycling with dye yam residue biochar production, the optimized scenario reduced waste disposal pressure, increased the value of dye yam residues, and enhanced long-term carbon storage (Fig. 6c). These findings demonstrate that this integrated strategy provides a practical pathway for coupling resource recycling, waste valorization, and climate change mitigation in traditional gambiered silk production.

3.4 Economic costs analysis

The economic cost of gambiered silk production was further evaluated for the three scenarios based on current raw material and energy prices in China. As shown in Fig. 7a, the total production cost of 350,000 m of gambiered silk in S1 was estimated to be 0.76 million USD. The cost structure was strongly dominated by labor, which accounted for 78.1% of the total cost, followed by *Dioscorea cirrhosa* Lour. at 18.2% (Fig. 7b). In contrast, electricity, iron-rich mud, and water contributed only 1.9%, 1.6%, and 0.3% (Fig. 7b), respectively. This cost distribution reflects the highly labor-intensive nature of gambiered silk production. Key production steps, including repeated dyeing, sun drying, mud application, and mud washing, still rely largely on manual operations and traditional expertise rather than mechanized processing (Wen et al. 2024). As a result, labor input represents not only the largest economic cost but also a critical

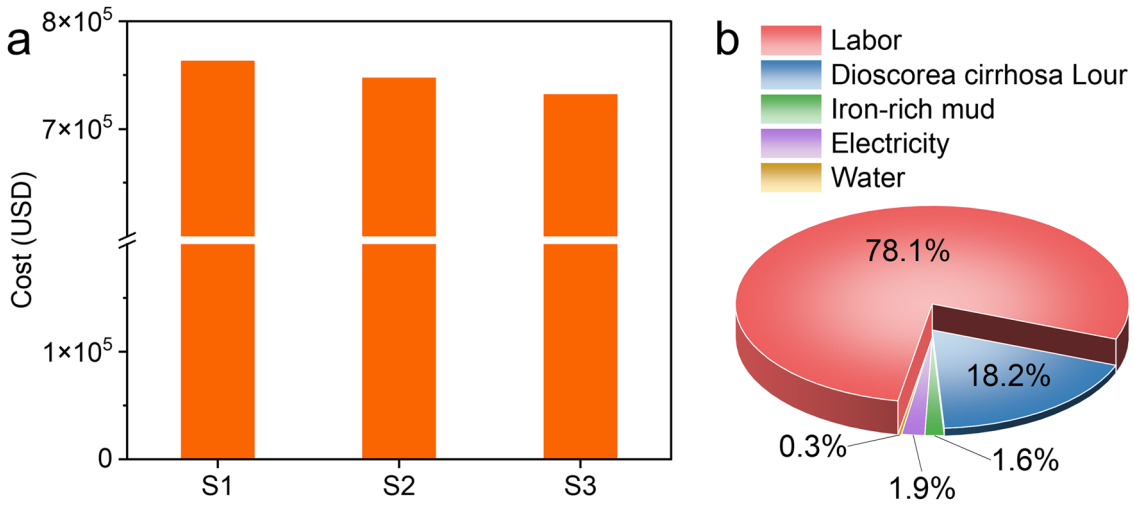


Fig. 7 The total economic cost of different scenarios (**a**) and cost structure of gambiered silk production (**b**)

component of the traditional craftsmanship that underpins the quality and unique characteristics of gambiered silk. Although resource and energy inputs contributed relatively little to the total economic cost, they remained important contributors to environmental impacts. This indicates that the economic and environmental hotspots of gambiered silk production are not fully aligned: labor dominates the cost structure, whereas energy and material use are more relevant to environmental performance. Therefore, future optimization should balance cost control, environmental improvement, and the preservation of traditional craftsmanship.

Compared with S1, S2 showed a slightly lower total production cost of 0.75 million USD (Fig. 7a), mainly due to the improved reuse of iron-rich river mud. River mud reuse reduced the demand for fresh mud extraction as well as the associated diesel and electricity consumption, thereby lowering mud-related costs. However, because iron-rich mud and energy inputs represented only small fractions of the total cost in S1, the overall cost reduction achieved in S2 was relatively limited. This suggests that river mud recycling is more effective in reducing environmental impacts than in substantially lowering economic costs. In S3, the conversion of dye yam residues into biochar further reduced the total cost (0.73 million USD) (Fig. 7a), making S3 the most economically favorable scenario among the three scenarios. This improvement was mainly attributed to the creation of additional value from dye yam residues, which are otherwise treated as low-value by-products or waste. By introducing biochar production, part of the production cost can be offset through product valorization, while residue disposal pressure is also reduced. Overall, these results indicate that river mud recycling provides moderate cost savings by improving resource efficiency, whereas biochar production offers greater economic potential by converting waste biomass into a value-added product. Therefore, the integrated strategy supports circular economy development and the sustainable upgrading of traditional gambiered silk production.

3.5 Sensitivity analysis

A sensitivity analysis was conducted to evaluate the effects of key operational variables on the LCA results (Song et al. 2018), focusing on two parameters: dye yam transportation distance and river mud reuse cycles. As shown in Fig. 8a, increasing the transportation distance from 200 to 800 km increased the ReCiPe endpoint score from approximately 14.1–17.9 kPt, with the increase mainly reflected in impacts on human health (Fig. S7a). This indicates that long-distance sourcing of dye yam can substantially increase the overall environmental impacts. Meanwhile, the carbon budget shifted from net carbon sequestration of approximately 27.0 t CO_2-eq to net carbon emissions of 4.7 t CO_2-eq as transportation distance increased (Fig. 8c), suggesting that transport-related emissions can gradually offset the carbon sequestration benefit provided by biochar production. This result highlights the importance of supply chain localization in gambiered silk production. Although converting dye yam residues into biochar can enhance carbon storage, the overall carbon budget is also influenced by the transportation distance of dye yam. Therefore, establishing nearby dye yam cultivation bases, reducing unnecessary long-distance transport, and improving regional supply chain coordination could effectively improve both environmental performance and carbon sequestration outcomes.

The number of river mud reuse cycles also had a strong influence on environmental impacts. As shown in Fig. 8b, increasing the river mud reuse cycles from ×1 to ×14 reduced the ReCiPe endpoint result from approximately 20.8 to 16.7 kPt, mainly due to lower impacts on human health and resource consumption (Fig. S7b). This indicates that repeated use of iron-rich river mud can effectively reduce the need for fresh mud extraction, thereby lowering associated diesel consumption, electricity demand, and extraction-related environmental impacts. The carbon budget also improved from net carbon emissions of approximately 38.0 t CO_2-eq at ×1 to net carbon sequestration of 6.0 t CO_2-eq at ×14 (Fig. 8d), indicating a shift from a carbon-emitting system to a carbon-sequestering system. However, the incremental environmental benefits gradually diminished with increasing reuse cycles, as the reduction in fresh river mud demand approached its limit, while the impacts associated with transportation, gambiered silk dyeing processes, and biochar production remained largely unchanged. Therefore, the optimal number of river mud reuse cycles should be determined by balancing environmental benefits against dyeing performance, regeneration time, product quality, and the operational demands of microbial reactivation, rather than simply maximizing reuse frequency. Overall, the sensitivity analysis highlights local dye yam sourcing and extended river mud reuse as key operational strategies for mitigating environmental impacts and promoting the low-carbon and sustainable development of gambiered silk production.

3.6 Implications of biochar strategies for sustainable gambiered silk production

Gambiered silk production has a long history in China and represents an important traditional natural dyeing craft with both cultural and economic value (Yang et al. 2018; Zhou et al. 2024). However, with the expansion of production and the increasing emphasis on green and low-carbon development (Zhang et al. 2023), improving

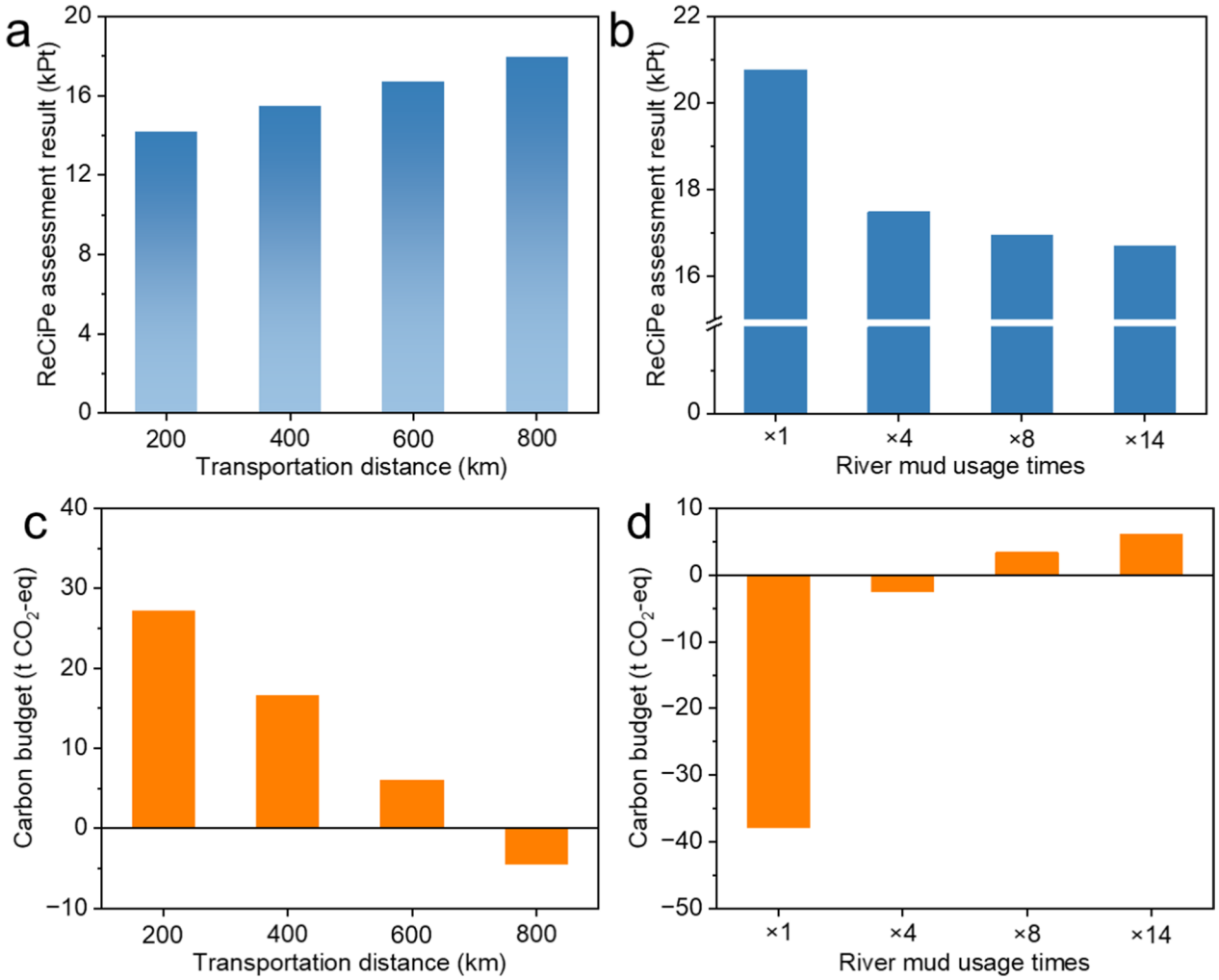


Fig. 8 Effects of dye yam transportation distance on ReCiPe endpoint environmental impacts (**a**) and carbon budget (**c**), and effects of iron-rich river mud reuse cycles on ReCiPe endpoint environmental impacts (**b**) and carbon budget (**d**)

the environmental and economic sustainability of gambiered silk dyeing has become increasingly important. The current gambiered silk production system depends heavily on fresh iron-rich river mud and large quantities of dye yam, while dye yam residues remain underutilized. Its environmental impacts are mainly associated with electricity consumption, fuel use, and long-distance transportation. The cyclic reuse of river mud reduces repeated mud extraction and associated energy consumption, thereby lowering both environmental impacts and production costs. Further conversion of dye yam residues into biochar slightly increases the overall environmental impact but provides additional carbon mitigation benefits through carbon sequestration while creating potential economic value. However, the current assessment also has several limitations. It partly relies on literature-based assumptions for river mud reuse and biochar carbon stability, and excludes the downstream treatment of dye yam residues. Future studies should validate these assumptions at pilot or industrial scale, quantify the long-term stability of dye yam residue-derived biochar, and refine the life cycle inventory with process-specific data.

At the industry scale, these optimization strategies could generate substantial cumulative benefits. The reported annual production of gambiered silk in China reached approximately 50 million meters, mainly concentrated in Guangdong and Guangxi Provinces. Based on field inventory data, producing 50 million meters of gambiered silk under the current process would place substantial demand on natural resources, requiring approximately 33,660 t of iron-rich river mud and 92,857 t of dye yam. River mud reuse could substantially reduce the demand for fresh mud extraction. Extending river mud reuse by one additional cycle would reduce the demand for fresh river mud by approximately 16,830 t,

while reuse for two additional cycles would increase this reduction to approximately 22,440 t. These results suggest that even incremental improvements in river mud reuse could produce considerable resource-saving and environmental benefits at the industry scale. Based on the carbon footprint results obtained from the 350,000 m functional unit, scaling up to an annual production volume of 50 million meters suggests that river mud recycling could reduce carbon emissions by approximately 6,258 t CO_2-eq compared with the current process. Moreover, the biochar production scenario could shift the system from net carbon emissions toward net carbon sequestration, with a scaled net carbon sequestration potential of approximately 857 t CO_2-eq. Although these estimates are based on linear extrapolation and should be further refined using complete industry-level inventory data, they demonstrate the large-scale mitigation potential of process optimization in gambiered silk production.

These findings provide broader insights into the role of resource recycling in promoting sustainable practices across traditional natural-dye-based textile production systems. The reuse of iron-rich river mud represents a practical resource-efficiency strategy by reducing repeated mud extraction, material inputs, and associated energy consumption. Meanwhile, converting dye yam residues into biochar offers a promising pathway for transforming waste biomass into value-added products with both economic and environmental benefits. Biochar can improve soil fertility, enhance nutrient retention, and promote agricultural productivity, thereby providing a sustainable soil amendment for agricultural applications (Hagemann et al. 2017). Moreover, its porous structure and abundant surface functional groups enable the adsorption and immobilization of various contaminants, supporting its potential application in heavy metal-contaminated soil remediation and wastewater treatment (Lian and Xing 2017; Qiu et al. 2022). These diverse environmental applications could create additional economic opportunities through the development of biochar-based soil amendments and remediation materials, increasing the commercial value of dye yam residues while reducing dependence on conventional waste treatment practices. Collectively, these strategies provide an integrated approach to resource conservation, waste valorization, and the sustainable development of traditional textile production.

4 Conclusion

This study assessed the environmental impacts, carbon budget, and economic performance of traditional gambiered silk production through life cycle assessment and life cycle cost analysis. The results revealed a total environmental impact of 14.06 kPt, with electricity consumption, transportation, and diesel use as the major contributors, while labor accounted for the largest share of production costs. Improving the reuse of iron-rich river mud in S2 reduced resource extraction and energy consumption, resulting in a 28.9% decrease in total environmental impact and a 30.7% reduction in carbon emissions. Although S3 introduced additional environmental impacts from biochar production, the resulting biochar provided a carbon sequestration benefit of 173 t CO_2-eq, shifting the system toward net carbon sequestration with a positive carbon budget of 6.0 t CO_2-eq. Sensitivity analysis indicated that the transport distance of raw dye yam and the number of river mud reuse cycles were key factors influencing environmental impacts and carbon emissions. Overall, converting dye yam residues into value-added biochar, complemented by river mud recycling, offers a promising strategy for carbon mitigation and enhancing the economic and environmental sustainability of traditional gambiered silk production.

Supplementary Information

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Supplementary Material 1.

Author contributions

Qing Li: Investigation, Writing—original draft. Jesvin Puay-Hwa Yeo: Formal analysis, Conceptualization. Liping Fang: Supervision. Kai Liu: Writing—review & editing, Funding acquisition. All authors read and approved the final manuscript.

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Data availability

The data that support this study are available from the corresponding author upon request.

Declarations

Ethics approval and consent to participate

This study was reviewed and approved by the Nanyang Technological University Institutional Review Board (NTU-IRB; Ref No.: IRB-2023-241; approval date: 5 October 2023). The approved study materials included the participant information sheet, informed consent form, interview questions, questionnaire questions, and recruitment materials. Informed consent was obtained from all participants prior to data collection. Permission was obtained for the use of fieldwork photographs included in this manuscript, and no personally identifiable information is disclosed. All procedures were conducted in accordance with the approved protocol and relevant ethical guidelines.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could appear to influence the work reported in this paper.

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References

Agnhage T, Perwuelz A, Behary N (2017) Towards sustainable *Rubia tinctorum* L. dyeing of woven fabric: how life cycle assessment can contribute. J Clean Prod 141:1221–1230. https://doi.org/10.1016/j.jclepro.2016.09.183

Bjørn A, Moltesen A, Laurent A, Owsianiak M, Corona A, Birkved M, Hauschild MZ (2018) Life cycle inventory analysis. In: Hauschild M, Rosenbaum R, Olsen S (eds) Life cycle assessment. Springer, Cham. https://doi.org/10.1007/978-3-319-56475-3_9

Carlsen L, Bruggemann R (2022) The 17 United Nations' sustainable development goals: a status by 2020. Int J Sustain Dev World Ecol 29:219–229. https://doi.org/10.1080/13504509.2021.1948456

Chen X, Lin B (2021) Towards carbon neutrality by implementing carbon emissions trading scheme: policy evaluation in China. Energy Policy 157:112510. https://doi.org/10.1016/j.enpol.2021.112510

Chen W, Meng J, Han X, Lan Y, Zhang W (2019) Past, present, and future of biochar. Biochar 1:75–87. https://doi.org/10.1007/s42773-019-00008-3

Chen J, Ma Y, Zhang X, Yan N, Li Y, Xu L, Lou Z (2025) Carbon footprint and environmental impact of reconstituted bamboo material based on life cycle assessment. J Clean Prod 523:146449. https://doi.org/10.1016/j.jclepro.2025.146449

Fazal ur R, Adeel S, Liaqat S, Hussaan M, Mia R, Ahmed B, Wafa H (2022) Environmental friendly bio-dyeing of silk using Alkanna tinctoria based Alkannin natural dye. Ind Crops Prod 186:115301. https://doi.org/10.1016/j.indcrop.2022.115301

Finkbeiner M, Inaba A, Tan R, Christiansen K, Klüppel H-J (2006) The new international standards for life cycle assessment: ISO 14040 and ISO 14044. Int J Life Cycle Assess 11:80–85. https://doi.org/10.1065/lca2006.02.002

Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R (2009) ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. The Hague, Ministry of VROM. ReCiPe

Gomez-Campos A, Vialle C, Rouilly A, Sablayrolles C, Hamelin L (2021) Flax fiber for technical textile: a life cycle inventory. J Clean Prod 281:125177. https://doi.org/10.1016/j.jclepro.2020.125177

Hagemann N, Joseph S, Schmidt H-P, Kammann CI, Harter J, Borch T, Young RB, Varga K, Taherymoosavi S, Elliott KW, McKenna A, Albu M, Mayrhofer C, Obst M, Conte P, Dieguez-Alonso A, Orsetti S, Subdiaga E, Behrens S, Kappler A (2017) Organic coating on biochar explains its nutrient retention and stimulation of soil fertility. Nat Commun 8:1089. https://doi.org/10.1038/s41467-017-01123-0

Hammar T, Peñaloza D, Hanning A-C, Haatanen N, Pakkasmaa J (2023) Life cycle assessment of textile fibre-to-fibre recycling by cellulose carbamate technology. J Clean Prod 426:139189. https://doi.org/10.1016/j.jclepro.2023.139189

He M, Xu Z, Hou D, Gao B, Cao X, Ok YS, Rinklebe J, Bolan NS, Tsang DC (2022) Waste-derived biochar for water pollution control and sustainable development. Nat Rev Earth Environ 3:444–460. https://doi.org/10.1038/s43017-022-00306-8

Huijbregts MA, Steinmann ZJ, Elshout PM, Stam G, Verones F, Vieira M, Zijp M, Hollander A, Van Zelm R (2017) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 22:138–147. https://doi.org/10.1007/s11367-016-1246-y

Ippolito JA, Cui L, Kammann C, Wrage-Mönnig N, Estavillo JM, Fuertes-Mendizabal T, Cayuela ML, Sigua G, Novak J, Spokas K, Borchard N (2020) Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. Biochar 2:421–438. https://doi.org/10.1007/s42773-020-00067-x

Jia X, Zhang Y, Tan RR, Li Z, Wang S, Wang F, Fang K (2022) Multi-objective energy planning for China's dual carbon goals. Sustain Prod Consum 34:552–564. https://doi.org/10.1016/j.spc.2022.10.009

Klöpffer W, Grahl B (2014) Life cycle assessment (LCA): a guide to best practice. John Wiley & Sons, Hoboken. https://doi.org/10.1002/9783527655625

Lehmann J, Cowie A, Masiello CA, Kammann C, Woolf D, Amonette JE, Cayuela ML, Camps-Arbestain M, Whitman T (2021) Biochar in climate change mitigation. Nat Geosci 14:883–892. https://doi.org/10.1038/s41561-021-00852-8

Li S, Cunningham AB, Shi Y, Qiu Z, Hartl A, Ding X, Wu S, Wang Y (2022) Blue to black: hypotheses on plant use complexity in traditional dyeing processes in Southeast Asia and China. Ind Crops Prod 188:115706. https://doi.org/10.1016/j.indcrop.2022.115706

Lian F, Xing B (2017) Black carbon (biochar) in water/soil environments: molecular structure, sorption, stability, and potential risk. Environ Sci Technol 51:13517–13532. https://doi.org/10.1021/acs.est.7b02528

Lin K, Wang Q, Huang X, Cao C, Tan B, Yang X, Li S, Meng B (2024) The investigation on dark dyeing properties of silk using *Dioscorea cirrhosa* Lour. tuber extracts with varied molecular weights. Text Res J 94:1909–1923. https://doi.org/10.1177/00405175241233740

Liu K, Fang L, Li F, Hou D, Liu C, Song Y, Ran Q, Pang Y, Du Y, Yuan Y, Dou F (2022a) Sustainability assessment and carbon budget of chemical stabilization based multi-objective remediation of Cd contaminated paddy field. Sci Total Environ 819:152022. https://doi.org/10.1016/j.scitotenv.2021.152022

Liu K, Ran Q, Li F, Shaheen SM, Wang H, Rinklebe J, Liu C, Fang L (2022b) Carbon-based strategy enables sustainable remediation of paddy soils in harmony with carbon neutrality. Carbon Res 1:12. https://doi.org/10.1007/s44246-022-00012-6

Matuštík J, Hnátková T, Kočí V (2020) Life cycle assessment of biochar-to-soil systems: a review. J Clean Prod 259:120998. https://doi.org/10.1016/j.jclepro.2020.120998

Pan Y, Xunan Y, Chen X, Xu M, Sun G (2017a) The right mud: studies in the mud-coating technique of Gambiered Guangdong silk. Appl Clay Sci 135:516–520. https://doi.org/10.1016/j.clay.2016.09.024

Pan Y, Yang X, Xu M, Sun G (2017b) The role of enriched microbial consortium on iron-reducing bioaugmentation in sediments. Front Microbiol 8:462. https://doi.org/10.3389/fmicb.2017.00462

Pan Y, Yang X, Xu M, Liang H, Xiao H, Huang D, Sun G (2018) Mechanism of dyeing technique of Xiang-yun-sha and bioaugmentation of its coating mud with iron reducing bacteria. Sci Sin Technol 48:1012–1020. https://doi.org/10.1360/N092018-00136

Pan Y, Yang X, Sun G, Xu M (2019) Functional response of sediment bacterial community to iron-reducing bioaugmentation with *Shewanella decolorationis* S12. Appl Microbiol Biotechnol 103:4997–5005. https://doi.org/10.1007/s00253-019-09816-w

Qiu M, Liu L, Ling Q, Cai Y, Yu S, Wang S, Fu D, Hu B, Wang X (2022) Biochar for the removal of contaminants from soil and water: a review. Biochar 4:19. https://doi.org/10.1007/s42773-022-00146-1

Roberts KG, Gloy BA, Joseph S, Scott NR, Lehmann J (2010) Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. Environ Sci Technol 44:827–833. https://doi.org/10.1021/es902266r

Saavedra-Rubio K, Thonemann N, Crenna E, Lemoine B, Caliandro P, Laurent A (2022) Stepwise guidance for data collection in the life cycle inventory (LCI) phase: building technology-related LCI blocks. J Clean Prod 366:132903. https://doi.org/10.1016/j.jclepro.2022.132903

Seo Y, Mori R, Ooyama S (2025) An integrated life cycle sustainability assessment of a traditional sake brewery in Japan: environmental, economic, and social perspectives – a case study. J Clean Prod 523:146352. https://doi.org/10.1016/j.jclepro.2025.146352

Smith P (2016) Soil carbon sequestration and biochar as negative emission technologies. Glob Change Biol 22:1315–1324. https://doi.org/10.1111/gcb.13178

Song Y, Hou D, Zhang J, O'Connor D, Li G, Gu Q, Li S, Liu P (2018) Environmental and socio-economic sustainability appraisal of contaminated land remediation strategies: a case study at a mega-site in China. Sci Total Environ 610–611:391–401. https://doi.org/10.1016/j.scitotenv.2017.08.016

Surjit R, Anusri Mahalakshmi B, Shalini E, Shubha Shree M (2023) Natural dyes in traditional textiles: a gateway to sustainability. In: Muthu SS (ed)

Natural dyes and sustainability. Springer Nature Switzerland, Cham, pp 1–24. https://doi.org/10.1007/978-3-031-47471-2_1
Vankar PS (2017) Natural dyes for textiles: sources, chemistry and applications. Woodhead Publishing, Cambridge. https://doi.org/10.1016/C2015-0-01885-8
Vieira MDM, Huijbregts MAJ (2018) Comparing mineral and fossil surplus costs of renewable and non-renewable electricity production. Int J Life Cycle Assess 23:840–850. https://doi.org/10.1007/s11367-017-1335-6
Wang J, Wang S (2019) Preparation, modification and environmental application of biochar: a review. J Clean Prod 227:1002–1022. https://doi.org/10.1016/j.jclepro.2019.04.282
Wen X, Liu C, Liao X, Jiang H (2024) Research on visual digital conservation and inheritance of dyeing and finishing techniques of Gambiered Canton Gauze. Zhuangshi 2024(12):92–100. https://doi.org/10.16272/j.cnki.cn11-1392/j.2024.12.018
Yang T, Guan J, Chen G, Tang R (2018) Instrumental characterization and functional assessment of the two-color silk fabric coated by the extract from *Dioscorea cirrhosa* tuber and mordanted by iron salt-containing mud. Ind Crops Prod 111:117–125. https://doi.org/10.1016/j.indcrop.2017.10.016
You S, Wang X (2019) On the carbon abatement potential and economic viability of biochar production systems: cost-benefit and life cycle assessment. In: Ok YS, Tsang DCW, Novak JM (eds) Biochar from biomass and waste. Elsevier, Amsterdam, pp 385–408. https://doi.org/10.1016/B978-0-12-811729-3.00020-0
Zhang L, Leung MY, Boriskina S, Tao X (2023) Advancing life cycle sustainability of textiles through technological innovations. Nat Sustain 6:243–253. https://doi.org/10.1038/s41893-022-01004-5
Zhong M, Huang S, Wang H, Huang Y, Xu J, Zhang L (2019) Optimization of ultrasonic-assisted extraction of pigment from *Dioscorea cirrhosa* by response surface methodology and evaluation of its stability. RSC Adv 9:1576–1585. https://doi.org/10.1039/C8RA07455K
Zhou X, Mayusoh C, Inkuer A, Puntien P (2024) The research on the development of cultural heritage: innovative design of gambiered Guangdong silk in Foshan. J Roi Kaensarn Acad 9:340–353