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Research article

Economic, environmental, and emergy analysis of China's green tea production

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ABSTRACT

Tea is one of the most popular beverages worldwide, and the sustainability of tea production is of vital strategic importance to tea farmers and stakeholders in its value chain. China is a global leader in tea consumption, production, and export. Here, we conduct a joint economic, life cycle, and emergy analysis to provide a comprehensive picture of the economic and environmental sustainability of China's local and exported tea (tea for domestic consumption vs for export). Although local tea is much more profitable than exported tea, it is also much more environmentally damaging, with impacts being 2.2–64.0 times higher, mainly because of lower yields. Specifically, the GHG emissions of local tea are about 6 times those of exported tea (49.90 vs 8.28 kg CO_2 eq/kg). A life-cycle-based scenario analysis indicates that the environmental impacts of China's local and exported tea can be substantially reduced (by 28–98%) by improving fertilizer use efficiency, adopting new varieties, and using renewable energy. Overall, our results show the environmental sustainability challenge of China's tea production and highlight the urgent need to take mitigation measures. Our study also provides important information for domestic and international tea beverage companies in their potential sustainable supply chain management of different tea products.

1. Introduction

Tea is one of the most popular beverages worldwide, but its environmental sustainability remains understudied. Globally, tea consumption has been rising steadily over the past few decades, along with economic development (Fig. 1). Today, per capita tea consumption is at ~35 l, only second to packaged water, and is projected to increase further in the near future, especially in large countries like China and India (Bolton, 2018). The tea industry is potentially energy- and emission-intensive, due to the use of large amounts of agrochemical inputs during tea cultivation and the use of traditional energy (such as firewood and coal) during tea processing (Ma et al., 2013; Taulo and Sebitosi, 2016). To improve the environmental sustainability of tea products requires quantitative assessments of how they affect the various aspects of the environment along the entire life cycle.

China is the world's largest tea producer, with annual output accounting for ~45% of the global total in 2018 (Fig. 1). It is also one of the three major tea exporters, the other two countries being Kenya and Sri Lanka. In total, the three countries produce ~60% of the world exports ("Food and Agriculture Organization (FAO). 2019," n.d.). China's tea exports have nearly doubled over the past three decades, from 0.20 in 1989 to ~0.36 million tons in 2018. China's domestic tea consumption increased even more dramatically, by 13-fold, from 0.15 in 1989 to 1.91 million tons in 2018 (*China Tea Yearbook.*, 2019). Despite the significant role China plays in global tea market, few studies have examined

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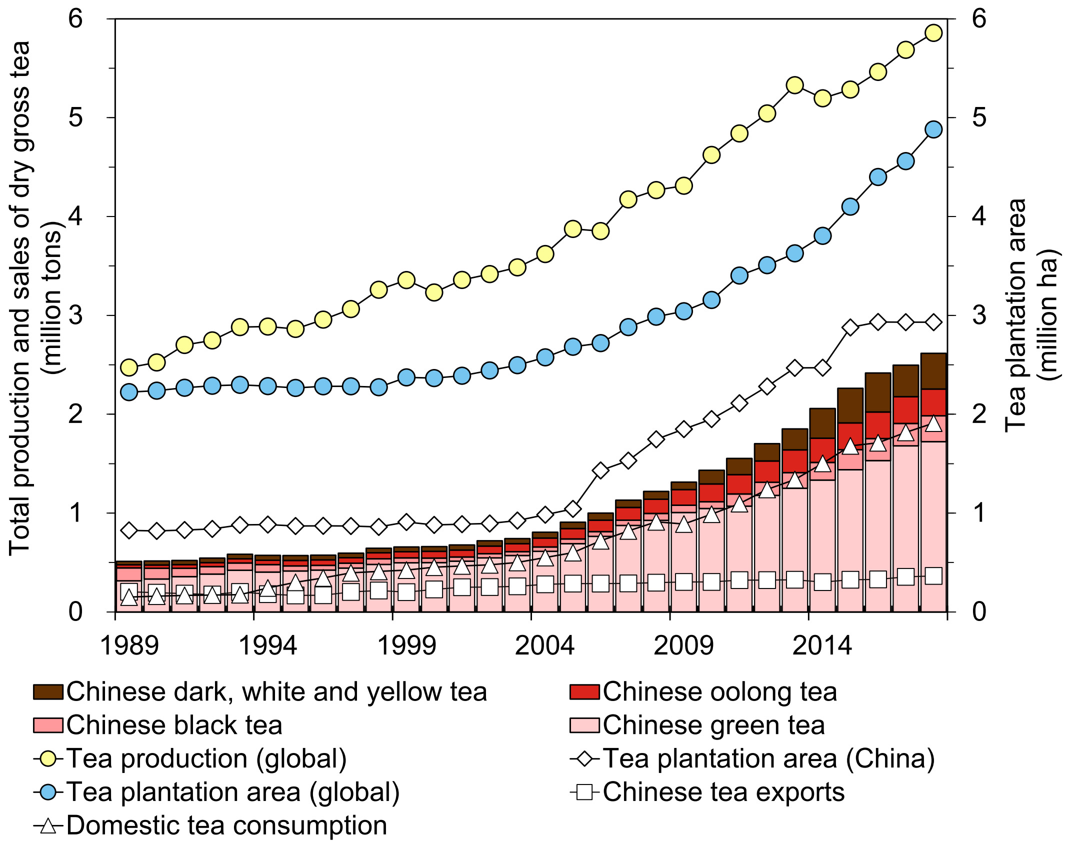

Fig. 1. Tea production and plantation area of China and the world, and Chinese tea trade during the past three decades.

the environmental sustainability of Chinese tea industry from cultivation to processing. Xu et al. studied the greenhouse gas (GHG) emissions and energy consumption of organic tea in China, but organic tea only accounts for <2% of the total output (Xu et al., 2019). Previous life-cycle assessments (LCAs) of several other countries (Azapagic et al., 2016; Cichorowski et al., 2015; Pelvan and Özilgen, 2017), such as Sari Lanka and India, are unlikely to represent China's tea production, considering the spatial variability of agroecosystems (Miller et al., 2006; Smith et al., 2017; Yang et al., 2018a). In addition, these LCAs have focused mainly on the climate change impact of tea products by quantifying their GHG emissions, and thus other environmental impacts associated with tea life cycle remain unclear. They have also shown that tea life-cycle GHG emissions vary substantially between countries, ranging from 0.6 to 21.5 kg CO_2 eq/kg dry tea, confirming the spatial variability and highlighting the need to conduct China's own research considering local cultivation and processing technologies.

Here, we report on the first comprehensive study of China's tea production considering the environmental, economic, and energetic aspects of tea cultivation and processing. Tea in China is categorized into six types: white, yellow, green, oolong, black, and dark tea (Zheng et al., 2015). In our study, we focused on green tea because it accounts for the largest share (Fig. 1) and is globally consumed for its widely recognized health benefits (Lecumberri et al., 2013). We further separated tea for domestic consumption from tea for export (termed local tea and exported tea hereinafter) and studied both products by surveying >100 tea farms and ~80 tea processing workshops. Given China's rich tea cultures, Chinese people have particular demands for tea qualities, including color, shape, scent, and taste (Zeng et al., 2013). For example, local tea is generally made from intact tender leaves or buds, whereas exported tea can be made from any tea leaves, tender or mature, intact or broken (Han et al., 2014). As a result, distinct differences arise in how the two tea products are harvested, leading potentially to their different environmental impacts. Furthermore, in our environmental LCA, we analyzed the mitigation potentials of three strategies, namely, improving fertilizer use efficiency, introducing new variety and using renewable energy for tea processing. We close by discussing the implications of our major findings. The specific aims of our study are to i) quantitatively evaluate and compare the economic characteristics, environmental impact, and emergy use of the two tea supply chains; ii) identify the hotspots of environmental impacts; and iii) analyze the mitigation potentials to explore optimization strategies for sustainable tea production.

2. Methods

2.1. Study area

Our study area is the Shengzhou city in Zhejiang Province, where tea cultivation covers an area of 11,000 ha and employs 82,000 farmers (or ~36% of all farmers in the area) (Xu, 2008). Most tea farms in Shengzhou are located in mountainous or semi-mountainous areas with a subtropical maritime monsoon climate. Rainfall is abundant with a mean annual precipitation of 1461 mm and a mean annual temperature of 16.4 °C. Shengzhou enjoys ~1990 sunshine hours and has a frost-free period of ~240 days in recent years. And its main soil types are red soil, yellow soil, yellow brown soil, acid purplish soil, regosol, and meadow

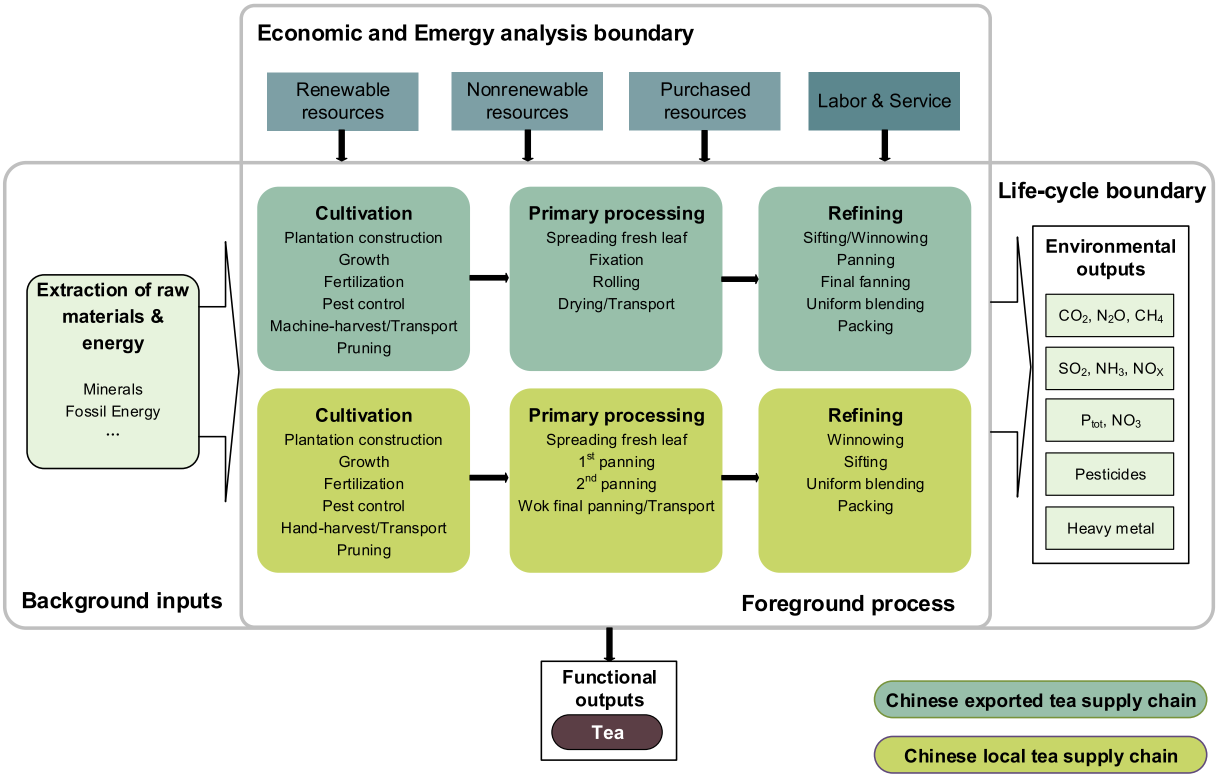

Fig. 2. The system boundary of local and exported green tea defined in this study for economic, life-cycle, and emergy analyses.

soil ("GB/T 17296-2009. Classification and codes for Chinese soil.," 2009). Most tea farms in Shengzhou are 0.9 ± 0.5 ha based on our survey, and have been in operation for more than 30 years. Note that a tea farm in this area can remain cultivated for more than 100 years if it is well managed and maintained. In 2017, Shengzhou produced >6,000 tons local tea and >60,000 tons of export tea, accounting for about two-thirds of the country's exports. Overall, Shengzhou's green tea production is representative of the national average situation partly because of its being a major green tea producer in China and partly because most tea farms in Shengzhou are owned by smallholders, a scale of tea production that is also typical of the country.

2.2. System boundary, major processes, and data sources

The system boundary selected for both exported and local tea production includes tea cultivation, primary processing, and refining (Fig. 2), and is applied consistently across the economic, life-cycle, and emergy analyses. Specifically, it is a cradle-to-gate system, starting from tea cultivation where various agricultural inputs from upstream are applied and ending at the refining factory gate. The reference year of our analyses is 2017.

During tea cultivation, fertilization is widely used to increase yields. The main fertilization method is top-dressing, and few farmers use deep application due to rising labor costs in recent years. Insecticides and fungicides are applied 2–3 times annually, while herbicides are forbidden by the local government to ensure the quality and safety of agricultural products. Irrigation is usually not used because tea-growing seasons are synchronized with rainfall in this area. The main difference in the agricultural management practice between local and exported tea is harvesting methods. Exported tea uses primarily mature leaves, which are harvested four times from mid-April to late October by a machine with one to six bud leaves plucked. Local tea uses primarily tender leaves or buds, which are harvested from mid-March to late April by hand with one to three bud leaves plucked. The use of hand-picking in local tea harvest is meant to best protect the integrity of the leaves. For local tea, because only buds or very tender leaves are harvested, its yields are substantially lower than those of exported tea (1,500 vs 21,000 kg/ha). Generally, tea plants are pruned once a year to prevent apical dominance and improve yields, and they enter a dormant period in winter, during which no agricultural operations are carried out.

After harvest, the fresh leaves are promptly transported to a primary processing factory over an average distance of 38 ± 14 km, and then dried with heat. Green tea processing differs little between the two products, except for the main energy source used for drying (coal for exported tea and electricity for local tea). The dried tea leaves contain impurities and need to be further processed in a refining factory. The main purposes of tea refining, based on some baking technologies, are to improve the appearance and quality (e.g., color, aroma, and taste).

Data on tea cultivation, primary processing, and refining stages were collected in 2017 from farmers and tea processing companies using formal questionnaires (see Table 4). Specifically, for the cultivation stage, data on agricultural inputs, fuel consumption, labor inputs, on-field emissions, and yields of fresh leaves were collected from the 105 tea farms, of which 60 targeted international markets and 45 domestic markets. For the primary processing stage, data on energy, packaging, and labor inputs for the exported and local tea were from 54 and 26 primary processing workshops, respectively. For tea refining, only large companies are involved in China. Thus, data on refining of the two tea products were obtained from the Zhejiang Huafa Tea Industry Co., Ltd., a company that specializes in tea export. The company has a number of continuous automatic production lines of green, black, and oolong tea, with an annual output of 10,000 tons of exported tea and 100 tons of local tea.

Table 1
Economic analysis of two tea supply chains at cultivation stage.

Item	Exported tea	Local tea
Aggregated input flows ($/ha/year)		
Natural resources	0.00	0.00
Seedlings	66.65	66.65
NKP fertilizer	577.62	577.62
Urea	166.62	133.30
Manure	466.54	–
Rapeseed cake	–	1110.81
Pesticide	79.98	133.30
Fuel & Lubricants	13.48	3.41
Machine & Equipment	355.46	133.30
Maintenance & Repairing	35.55	13.33
Harvest transportation	48.58	3.41
Direct labor	1336.38	7401.43
Total cost	3146.72	9576.56
Output		
Fresh leaves (kg/ha)	3110.28	222.16
Revenue ($/ha/year)	4665.42	14440.59
Economic indices		
Profit ($/ha/year)	1518.56	4863.89

Table 2
Economic analysis of two tea supply chains at primary processing stage. Unit: $/kg dry tea.

Item	Exported tea	Local tea
Aggregated input flows		
Fresh leaves	0.93	40.43
Electricity	0.03	0.70
Coal	0.16	0.00
Machine & Equipment	0.10	0.19
Buildings	0.01	0.04
Construction investment	0.01	0.06
Maintenance & Repairing	0.00	0.01
Transportation	0.07	0.07
Direct labor	0.30	0.74
Total cost	1.64	42.26
Output		
Revenue	1.78	45.91
Economic indices		
Profit	0.14	3.66

Table 3
Economic analysis of two tea supply chains at refining processing stage. Unit: $/kg dry tea.

Item	Exported tea	Local tea
Aggregated input flows		
Gross tea	1.78	47.54
Electricity	0.01	0.02
Coal	0.01	–
Machine & Equipment	0.01	0.01
Packing	0.02	2.96
Buildings	0.03	0.03
Construction investment	0.01	0.03
Maintenance & Repairing	0.01	0.01
Direct labor	0.12	0.81
Rent	0.01	0.01
Total cost	2.05	49.84
Output		
Revenue	2.96	118.49
Economic indices		
Profit	0.91	68.64

2.3. Economic analysis

We conducted a simple economic cost-benefit analysis to evaluate the profit of the two tea products:

$$Profit = revenue - \sum_{i=1}^{i=n} P_i \times f_i i = 1,\ 2,\ \ldots,\ n \quad (1)$$

where the *profit* equals the difference between *revenue* and *the total cost*, which is the sum of the cost of individual inputs. f_i is the ith input flow of material, energy, or labor and P_i is the unit price of the ith flow. Details on the price of agricultural inputs, packings, and energy use at different stages are shown in Tables 1–3.

2.4. Life cycle assessment (LCA) and mitigation scenarios

The LCA approach used in this study follows the guidelines in ISO 14040/44 (ISO, 2006a, b) and PAS 2050 (BSI and Carbon Trust, 2011). LCA procedure is divided into three steps: goal and scope definition, inventory analysis, and life cycle impact assessment.

2.4.1. Goal and scope definition

The main goal of this study is to estimate the environmental impacts of production of Chinese tea and to identify opportunities for improvements. We broke the three life-cycle stages described above down into 15 processes for exported tea and 14 for local tea (Fig. 2). We defined the functional unit (FU) as 1 kg of (dry and refined) tea produced at the factory gate; for both tea products, 4.2 kg of fresh leaves are needed to produce 1 kg of dry and refined tea (Table 4). Data on tea seedlings were from one local tea nursery. The tea nursery is a one-time activity; we thus annualized the direct inputs and outputs used in nursery, assuming a 30-year duration, and allocated them to the harvesting phase (Table 5). We excluded agricultural machinery (e.g., trimming and tea-plucking machines) and capital equipment (e.g., factory buildings) in our analysis as they generally contribute a small fraction to annual emissions after amortization (Hill et al., 2006; Yang et al., 2012). We also excluded soil carbon storage. Although tea cultivation can increase soil carbon stocks, the rate of carbon storage tends to slow down and approach zero after 30 years (Wang et al., 2019) and as described above most of the farms we surveyed have been in cultivation for about 30 years.

2.4.2. Inventory data

The life cycle inventory analysis includes: (1) direct emissions from each life cycle stage, including application of chemical fertilizers and pesticides and combustion of fuels (Table 6) and (2) upstream emissions embedded in various inputs, including urea and NPK compound fertilizers, organic fertilizers, rapeseed meal, pesticides, and packaging materials. Data for all the upstream emissions were from the Ecoinvent database (v2.2). Specifically, soil N_2O emissions were estimated using an average emission factor of 3.09% of N input based on previous field measurements (Chen et al., 2017; Han et al., 2013; Yao et al., 2018). NO_x emissions were estimated as a fraction (21%) of N_2O emissions (Nemecek and Schnetzer, 2011). NH_3 emissions were estimated based on an emission factor of 11.14% of total N quantity (Wang et al., 2016). Based on Ma et al. (2012), emission factors for NO_3–N and PO_4–P were 0.1% and 0.2% of total N and P inputs, respectively. The percentages of pesticides released to the air, water, and soil were 10%, 1%, and 43%, respectively (van Calker et al., 2004). Data on heavy metals contained in fertilizers and crops were derived from literature (Wang and Ma, 2004). Emissions from diesel combustion came from reference (Liang, 2009) and emissions from coal combustion were derived from the Ecoinvent database (v2.2). In order to improve the transparency of the inventory data, we have shown how the input / output processes have been modeled in LCA (Table S11 and S12).

Only the main agricultural materials and transport routes were considered in the stage of transport and distribution. Information on the routes, transport types, and average distances is listed in Table S10 (SI), and was obtained from tea farmers and producers.

Table 4
Inputs and outputs of the exported and local tea supply chains.

	Items	Unit	Exported tea Average	Min.	Max.	SD	Local tea Average	Min.	Max.	SD
Cultivation (/ha/year)										
Inputs	Seedlings	kg	140	-	-	-	140	-	-	-
	Urea	kg	750	300	1800	304	600	0	1200	253
	NPK fertilizer	kg	1500	375	3000	598	1500	300	3000	676
	Manure	kg	1800	1600	2400	353	-	-	-	-
	Rapeseed meal	kg	-	-	-	-	3000	0	4500	1570
	Pesticide	L	1.50	1.25	3.75	1.03	3.75	1.50	4.50	0.94
	Fungicide	L	1.20	0.00	1.75	0.55	0.75	0.00	3.50	0.82
	Diesel	kg	76	68	82	9.8	19	15	30	4.86
	Direct labor	h	602	550	750	52	7802	7500	9000	1631
Outputs	Fresh leaves	kg	21000	19875	21750	1497	1500	900	1650	262
Primary processing (/kg dry tea)										
Inputs	Fresh leaf	kg	4.20	3.90	4.80	0.43	4.20	4.10	5.50	0.78
	Electricity	kWh	0.24	0.17	0.31	0.03	5.50	3.90	9.20	1.64
	Coal	kg	1.13	0.55	1.94	0.28	-	-	-	-
	Polypropylene bag	g	0.42	0.33	0.74	0.01	0.54	0.30	0.81	0.17
	Direct labor	h	0.14	-	-	-	0.19	-	-	-
Outputs	Gross tea	kg	1.00	-	-	-	1.00	-	-	-
	Waste leaf	g	0.5	-	-	-	0.5	-	-	-
Refining processing (/kg dry tea)										
Inputs	Gross tea	kg	1.00	-	-	-	1.00	-	-	-
	Electricity	kWh	0.05	-	-	-	0.14	-	-	-
	Coal	kg	0.07	-	-	-	-	-	-	-
	Polypropylene bag	g	0.12	-	-	-	0.12	-	-	-
	Paper packings	g	168	-	-	-	120	-	-	-
	Direct labor	h	0.003	-	-	-	0.100	-	-	-
Outputs	Dry tea	kg	1.00	-	-	-	1.00	-	-	-

Min.: minimum; Max.: maximum; SD: Std. deviation.

Table 5
Annual inputs used in the tea nursery (/ha/year).

Items	Units	Amount
Tea stem (cuttage)	kg	11300
NPK fertilizer	kg	1200
Organic fertilizer	kg	750
Pesticide	kg	5.4
Bamboo	kg	6750
Shading net (Polypropylene)	kg	90
Electricity	kwh	440
Direct labor	labor h	9540

It is assumed that the tea seedlings used for exported tea and local tea are the same.

Table 6
On-field emissions at tea cultivation stage (/ha/year).

Items	Unit	Exported tea	Local tea
Emissions to air			
CO_2	kg	62.68	243.05
N_2O	kg	32.04	31.61
CH_4	g	0.14	0.53
CO	kg	0.01	0.05
SO_x	kg	0.08	0.30
NO_x	kg	6.82	7.00
NH_3	kg	89.50	88.06
Bifenthrin	kg	0.15	0.375
Chlorothalonil	kg	0.12	0.075
Emissions to surface water			
NO_3^-	kg	2.92	2.88
Ptot	kg	0.06	0.05
Bifenthrin	kg	0.015	0.038
Chlorothalonil	kg	0.012	0.007
Emissions to soil			
Bifenthrin	kg	0.645	1.613
Chlorothalonil	kg	0.516	0.323
Pb	g	4.41	3.72
Cd	g	0.41	0.39
Cu	g	16.54	16.47
Zn	g	522.82	522.71

For the transport of tea fresh leaves and gross tea, the distance between tea plantation and the primary processing factory is 38 km on average, and the distance between the primary processing factory and the refining factory is 27 km.

2.4.3. Life cycle impact assessment

For impact assessment, we applied the CML2001 method (Guinée et al., 2001). We focused on six environmental impact categories closely related to agro-industrial food production, namely, global warming potential (GWP) (100 years), acidification potential (AP), eutrophication potential (EP), aquatic ecotoxicity (AT), human toxicity (HT), and terrestrial ecotoxicity (TT). In addition, cumulative energy demand (CED) was used to determine the consumption of nonrenewable fossil energy. Normalization and weight factors of potential environmental impacts are shown in Table S1.

2.4.4. Scenario analysis

We performed a scenario analysis to qualify the energy-saving and emission-reduction potentials of tea production (Fig. 5). We considered two short-term scenarios reflecting improved fertilizer use efficiency and adoption of new varieties, and one relatively longer-term scenario reflecting the use of renewable energy in lieu of thermal energy either on site or as a result of greater penetration of renewable in China's power grids. Currently, tea production in China consumes an average of 420 kg N per ha, but research has shown that lower rates of 350-400 kg N/ha are sufficient (Ma et al., 2013). Thus, we assumed an average N application rate of 375 kg N/ha in the fertilizer use efficiency scenario. Research has also shown that new tea varieties can increase yields by 20% (Xu et al., 2019), a rate we adopted in the new varieties scenario. In the renewable energy scenario, we assumed that coal and thermal power in the benchmark were replaced by solar energy. We also quantified the cumulative effects of adopting all three measures.

2.4.5. Sensitivity analysis

A sensitivity analysis was conducted to explore the robustness of LCIA results for the two tea products. Specifically, the effects of variation of key parameters, namely, N_2O, NH_3, chemical fertilizer, rapeseed meal, coal, and electricity, were used to test the LCIA results (Fig. S2–S3).

2.5. Emergy analysis

As a bridge between environmental and economic systems, emergy analysis (Odum, 1996) is particularly suited for evaluating systems at the interface between the "natural" and "human" systems, such as agroecosystems (Cuadra and Rydberg, 2006). Solar emergy is defined as the amount of available energy (expressed as solar equivalents) directly or indirectly required to support a given system (Odum, 1996, 1983). The unit of solar emergy is solar emjoules, abbreviated as sej. The emergy requirement per unit of output (be it energy, matter, labor, or currency) is named unit emergy value (UEV) and measured as sej/unit (sej/j, sej/g, sej/h, sej/$). The emergy of a system is calculated by the following equation:

$$Emergy = \sum_{i=1}^{i=n} UEV_i \times f_i \; i = 1, \; 2, \; \ldots, \; n, \qquad (2)$$

where *Emergy* is the total solar emergy supporting the system, f_i is the ith input flow of matter energy or labor, and UEV_i is the unit emergy value of the ith flow (based on literature or our own estimates). All energy sources are categorized into three types: i) free local renewable resources (L_R), such as sun and rain; ii) free local nonrenewable resources (L_N), such as topsoil loss; and iii) economic feedbacks resources (F), which are from outside the studied agroecosystem and in our study include fertilizers, pesticides, energy, and packaging materials used for tea cultivation and processing (Fig. S1). The inputs that entered the systems were divided into renewable and nonrenewable fractions using their respective renewability factors (RNF, %R). The emergy analysis tables are shown in Table S2–S4. UEVs and RNFs used in this study are shown in Table S5. The updated global emergy baseline used in our analysis was 12.0×10^{24} sej/year (Brown and Ulgiati, 2016). Meteorological data of Shengzhou City were acquired from the China Meteorological Information Center ("China National Meteorological Information Center," 2020). The energy conversions of each item were derived from a prior study (Luo, 2001). The estimation of emergy exchange ratio, the fair price of exported tea, and the potential environmental service (Ep) can be found in Table S13.

3. Results

3.1. Profitability of local and exported tea

Based on our cost-benefit analysis, we find that local tea is considerably more lucrative, valuable, and profitable than exported tea (Table 7). Farmers earn only 0.30 $/kg per kg of exported tea, but 13.62 $/kg per kg of local tea. Of all the three main stages, tea refining is most profitable. The total cost of local tea (49.84 $/kg) is 24 times higher than that of exported tea (2.05 $/kg), and its revenue is 40 times higher (118.49 vs 2.96 $/kg). As a result, the profit of local tea is 75 times higher than that of exported tea (68.64 vs 0.91 $/kg). A main driver of the cost of tea in China, especially for local tea, is labor. The total labor inputs for local tea are 82 times higher than those for exported tea (22.14 vs 0.27 labor h/kg), because hand-plucking involved in local tea harvest is extremely labor-intensive (21.85 labor h/kg). At the cultivation stage, the costs of labor contribute the most, with 43% in exported tea and 77% in local tea.

Table 7
The economic characteristics of the exported tea and the local tea (unit: $/kg).

	Exported tea	Local tea
Cultivation		
Total cost	0.63	26.81
Revenue	0.93	40.43
Profit	0.30	13.62
Primary processing		
Total cost	1.64	42.25
Revenue	1.78	45.91
Profit	0.14	3.66
Refining		
Total cost	2.05	49.84
Revenue	2.96	118.49
Profit	0.91	68.64

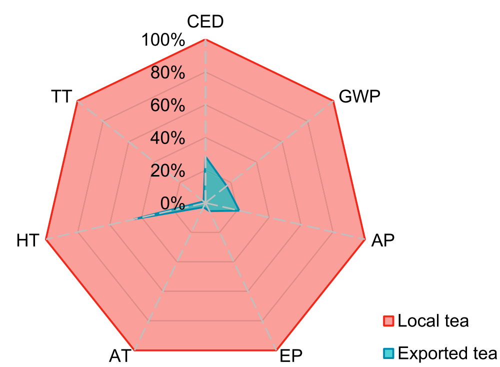

Fig. 3. Difference of the characterization results between Chinese local and exported tea.

Table 8
The environmental impacts of the exported tea and the local tea.

Environmental impact	Unit	Exported tea	Local tea
Cumulative energy demand	MJ eq/kg	94.10	330.71
Global warming potential	kg CO_2 eq/kg	8.28	49.90
Acidification potential	kg SO_2 eq/kg	0.13	0.61
Eutrophication potential	kg PO_4 eq/kg	0.01	0.19
Aquatic ecotoxicity	kg 1,4-DB eq/kg	1.02	35.70
Human toxicity	kg 1,4-DB eq/kg	3.34	7.46
Terrestrial ecotoxicity	kg 1,4-DB eq/kg	0.04	2.83

3.2. Environmental sustainability of tea production

3.2.1. Life-cycle environmental impacts and main contributors

The environmental impacts of local tea are also much greater than those of exported tea (Fig. 3). First, the GHG emissions of local tea are about 6 times those of exported tea (49.90 vs 8.28 kg CO_2 eq/kg) (Table 8). The much higher GHG emission rate of local tea is caused primarily by its low yields (of tender leaves and buds). As a result, the cultivation stage of local tea dominates its total GHG emissions, with 42.93 kg CO_2 eq per kg of tea produced, and primary processing and refining add another 6.51 and 0.40 kg CO_2 eq/kg, respectively (Tables S6–S9). For exported tea, cultivation, primary processing, and refining contribute 2.91, 4.35, and 1.02 kg CO_2 eq/kg, respectively.

In addition to GHG emissions, other environmental impacts of local tea are also greater than those of exported tea. The cumulative energy demand of local tea is >3 times higher than that of exported tea (330.71 vs 94.10 MJ eq/kg). The acidification and eutrophication impacts of local tea are >4 and >14 times higher than those of exported tea (0.61 vs 0.13 kg SO_2 eq/kg and 0.19 vs 0.01 kg PO_4 eq/kg). The acidification impacts of two tea products are mainly from primary processing and cultivation, whereas culti-

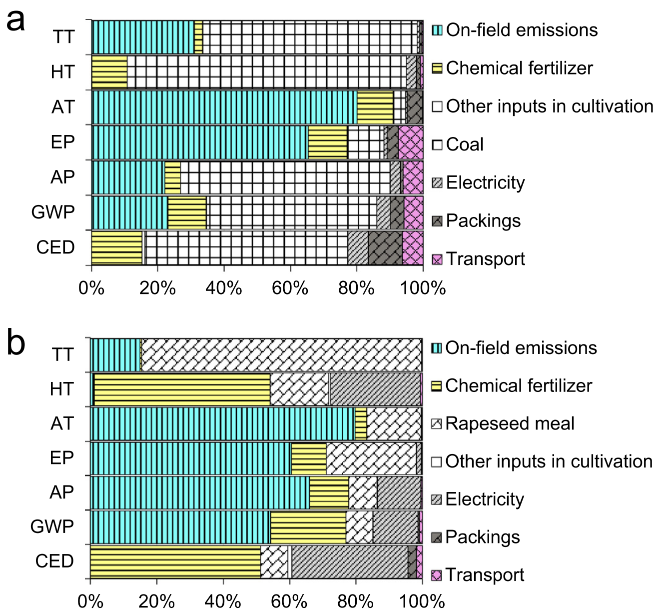

Fig. 4. Main contributors to the environmental impacts of (a) the exported and (b) local tea.

vation is the major source of eutrophication impact (Tables S6–S9). The aquatic ecotoxicity, human toxicity and terrestrial ecotoxicity of local tea are about >35, 2, and 64 times higher than those of exported tea, respectively (35.70 vs 1.02 kg 1,4-DB eq/kg, 7.46 vs 3.34 kg 1,4-DB eq/kg and 2.83 vs 0.04 kg 1,4-DB eq/kg). For local tea, cultivation is the principal cause of the three toxicity impacts, namely, 99% to aquatic ecotoxicity, 72% to human toxicity, and 99% to terrestrial ecotoxicity. For exported tea, cultivation contributes 91% to aquatic ecotoxicity and tea primary processing contributes 82% to human toxicity and 62% to terrestrial ecotoxicity.

More specifically, for exported tea, coal use (mainly from primary processing) is the dominant cause of cumulative energy demand, GHG emissions, acidification, human toxicity, and terrestrial ecotoxicity, accounting for 51–84% of total impacts (Fig. 4a). On-field emissions at cultivation stage are another important cause especially for eutrophication and aquatic ecotoxicity, accounting for 65% and 80% of the total impacts, respectively. The production of chemical fertilizer also contributes significantly to several environmental impacts (e.g., 15% to cumulative energy demand and 12% to eutrophication). Similarly, for local tea, on-field emissions contribute 54–80% to GHG emissions, acidification, eutrophication, and aquatic ecotoxicity (Fig. 4b). Fertilizer (chemical fertilizer and rapeseed meal) is a principal cause of all the environmental impacts. For example, chemical fertilizer contributes 51% to cumulative energy demand, 23% to GHG emissions, and 53% to human toxicity, and rapeseed meal contributes 84% to terrestrial ecotoxicity, mainly due to the application of large amounts of pesticides during rape cultivation. Electricity use (mainly from tea primary processing) also contributes substantially to cumulative energy demand and human toxicity (i.e., 35% and 27%, respectively).

3.2.2. Comparison with literature

As shown in Table 9, most studies mainly focused on GWP and showed estimates ranging from 1.99 to 21.53 kg CO_2 eq/kg (Xu et al., 2019). The estimated GWP of exported tea in this study (8.28 kg CO_2 eq/kg) was within this range, whereas local tea has an absolutely high GWP of 49.90 kg CO_2 eq/kg. The PAS 2050 classifies emissions in a range of > 5 kg CO_2 per kg of product as "highly intensive" (DEFRA, 2011). Based on this classification, both tea products in this study are technically considered a very high-

Table 9
Summary of studies linking environmental impacts of the tea sector.

Reference	Tea	Region [a]	Functional unit	System boundary [b] PS1	PS2	PS3	PS4	PS5	Environmental impact [c]
This study	Local/Export green tea	ZJ, China	1 kg	✓	✓	✓			CED, GWP, AP, EP, AT, HT, TT
Hu et al., 2019	Black tea	TW, China	1 kg	✓		✓	✓	✓	GWP
Xu et al., 2019	Black, green and oolong tea	ZJ, China	1 kg, 1 cup	✓	✓	✓	✓	✓	CED, GWP
Soheili-Fard et al., 2018	Black tea	Iran	1 cup	✓		✓	✓	✓	GWP, ADP, AP, EP, ODP, HT, AT, MT, TT, POFP
Vidanagama and Lokupitiya, 2018	Unknown	Sri Lanka	1 t	✓		✓			GWP
Khanali et al., 2017	Black, green and oolong tea	Iran	1 t	✓		✓			GWP, ADP, AP, EP, ODP, HT, AT, MT, TT, POFP
Kouchaki-Penchah et al., 2017	Unknown	Iran	1 t	✓					GWP, ADP, AP, EP, ODP, HT, AT, MT, TT, POFP
Pelvan and Özilgen, 2017	Black tea	Turkey	1 t	✓		✓			CED, GWP
Munasinghe et al., 2017	Orthodox/CTC black tea	Sri Lanka	1 kg	✓		✓			CED, GWP
Taulo and Sebitosi, 2016	Black tea	Malawi	1 kg			✓			GWP, AP, EP, HT, POFP
Azapagic et al., 2016	Black tea	Kenya	1 kg, 1 cup	✓	✓	✓	✓	✓	GWP
Cichorowski et al., 2015	Darjeeling black Tea	India	1 kg, 1 L	✓	✓	✓	✓	✓	GWP
Jefferies et al., 2012	Black tea	AFRAS	A carton of 50 g tea	✓		✓	✓	✓	WD
Doublet and Jungbluth 2010	Darjeeling black Tea	India	1 cup	✓		✓	✓		CED, GWP

[a] Region: ZJ, Zhejiang Province; TW, Taiwan; AFRAS, Africa and Asia region.
[b] PS: production stage: PS1, raw material acquisition; PS2, tea cultivation; PS3, tea processing; PS4, tea consumption; PS5, disposal.
[c] Environmental impact: Global warming potential (GWP); cumulative energy demand (PED); water demand (WD); abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), ozone layer depletion potential (ODP), human toxicity (HT), fresh water aquatic ecotoxicity (AT), marine aquatic ecotoxicity (MT), terrestrial ecotoxicity (TT), and photochemical oxidation formation potential (POFP).

intensity source of emissions. Notably, tea plantations in Asian countries have been reported to have released more N_2O into the atmosphere through nitrification or denitrification than other staple food crops, which can be explained by a large amount of fertilizer applied (Tokuda et al., 2001; Huang et al., 2014; Zhu et al., 2014). Moreover, very few available studies reported the CED, AP, EP, and HT of tea were 18.4−30.5 MJ eq, 0.002−0.01 kg SO_2 eq, 0.001−0.003 kg PO_4 eq, and 0.03−0.26 kg 1,4-DCB eq/kg dry tea, respectively, which were all lower than the values obtained in this study (Taulo et al., 2016; Kouchaki-Penchah et al., 2017; Soheili-Fard et al., 2018). A comparative basis is lacking due to limited research on other environmental impacts of related tea products worldwide. Direct and constructive conclusions by comparison with other studies is difficult to make due to different consumptions, system boundaries, and databases. However, the high environmental impacts of tea in this study are mainly due to on-field emissions of cultivation stage being included. As shown in Table 6, most studies excluded the cultivation stage of all the available 14 studies. For example, Kouchaki-Penchah et al. (2017) and Khanali et al. (2017) evaluated the GWP, AP, and EP of tea, which are closely related to N_2O and NH_3 emissions and NO_3^- leaching. However, they only considered the stage of agri-material acquisition and tea processing, complex soil physical and chemical processes at the tea cultivation stage are neglected. In this study, using GWP as an example, if excluding the field emissions of tea cultivation, the GWP of the exported tea and local tea will be decreased by 23.1% and 12.6% respectively. Thus, a well-established LCA study on tea must include field emissions during cultivation.

3.2.3. Mitigation scenarios

The strategies proposed can effectively save energy and reduce environmental emissions for both tea systems (Fig. 5). The use of renewable energy can greatly save cumulative energy demand by 62% for exported tea and 34% for local tea. Improving fertilizer use efficiency and introducing new tea varieties can reduce cumulative energy demand by 3%-5% for exported tea and 10%-26% for local tea. The adoption of all three strategies can save 70% of cumulative energy. For GHG, improving fertilizer use efficiency and utilizing renewable energy can greatly reduce total emissions by 34%-51% for exported tea and 13%-55% for local tea. And planting new tea varieties can reduce GHG emissions by 6% and 14% for exported tea and local tea. Adopting all three strategies can reduce total emissions by 82-91% for both tea products. For acidification, improving fertilizer use efficiency and utilization of new varieties and renewable energy can reduce the impact by 32%, 4%, and 62% for exported tea, and by 52%, 14%, and 13% for local tea. Adopting all three strategies can reduce acidification emission by 79%-98% for the two teas. For eutrophication, improving fertilizer use efficiency can greatly reduce the impact by 34% and 60% for exported tea and local tea. The use of new varieties and renewable energy can reduce eutrophication by 10%-13% for exported tea and 1%-16% for local tea. The adoption of all three strategies can reduce 57%-77% of eutrophication for both tea products. For aquatic ecotoxicity, improving fertilizer use efficiency and utilization of new varieties and renewable energy can reduce the impact by 4%, 15%, and 10% for exported tea, and by 10%, 17%, and 1% for local tea. Adopting all three strategies can reduce acidification emission by 28%-29% for the two teas. For human toxicity, utilizing renewable energy can greatly reduce the impact by 79% for exported tea and 25% for local tea. Improving fertilizer use efficiency and introducing new tea varieties can reduce human toxicity by 2%-4% for exported tea and 12% for local tea. The adoption of all three strategies can reduce the total impact by 85% for exported tea and 49% for local tea. For terrestrial ecotoxicity, improving fertilizer use efficiency and utilization of new varieties and renewable energy can reduce the impact by 7%, 6%, and 61% for exported tea, and by 45%, 17%, and 1%

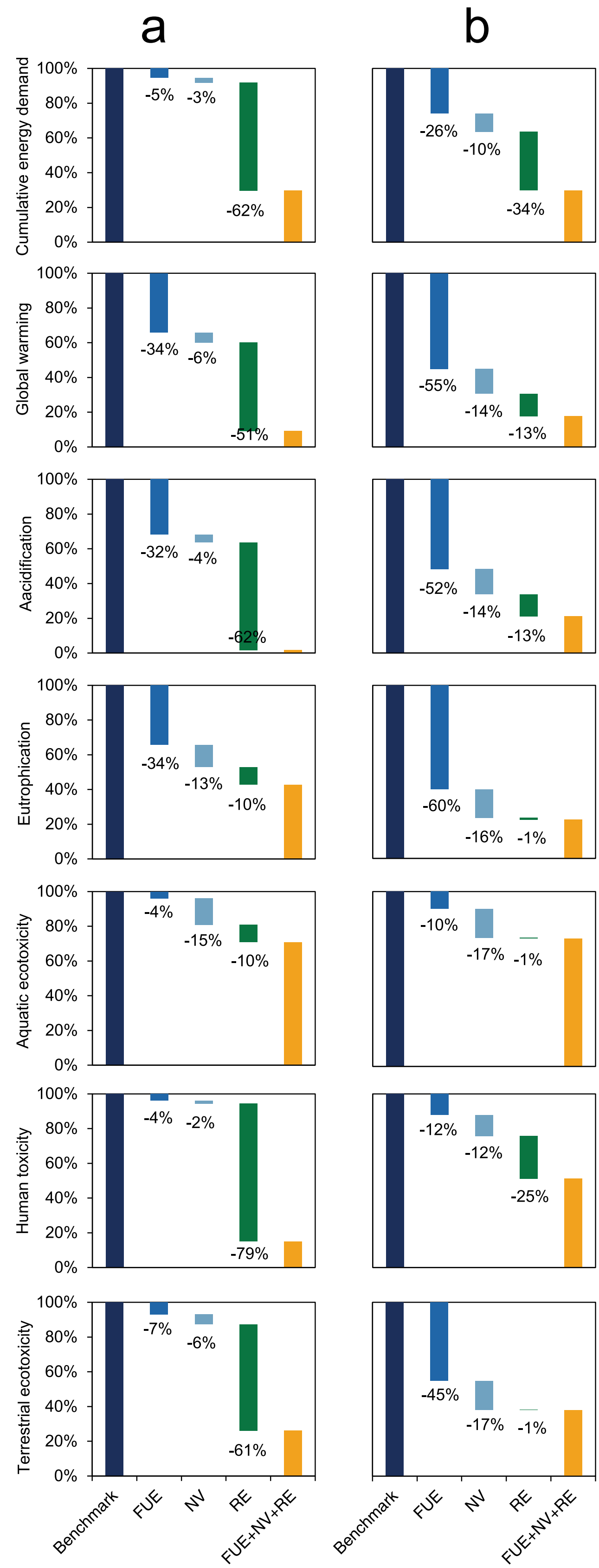

Fig. 5. Mitigation potentials for China's exported tea (a) and local tea (b). FUE, fertilizer use efficiency; NV, new variety; RE, renewable energy. FUE+NV+RE (cumulative effect).

Table 10
Aggregate emergy flows of two tea production systems (sej/kg/year).

Aggregate emergy flows	Exported tea	%	Local tea	%
Free local renewable resources (L_R)	3.37×10^{11}	3.3%	4.72×10^{12}	1.8%
Free local nonrenewable resources (L_N)	2.79×10^{10}	0.3%	3.90×10^{11}	0.2%
Purchased inputs (P)	6.98×10^{12}	68.0%	2.20×10^{14}	84.9%
Services (S)	2.92×10^{12}	28.4%	3.40×10^{13}	13.1%
Purchased commodity and services (F = P+S)	9.90×10^{12}	96.4%	2.54×10^{14}	98.0%
Renewable fraction of economic feedbacks resources (F_R)	4.12×10^{11}	4.0%	2.49×10^{13}	9.6%
Nonrenewable fraction of economic feedbacks resources (F_N)	9.49×10^{12}	92.4%	2.29×10^{14}	88.4%
Renewable emergy flows (L_R+F_R)	7.49×10^{11}	7.3%	2.97×10^{13}	11.5%
Nonrenewable emergy flows (L_N+F_N)	9.52×10^{12}	92.7%	2.29×10^{14}	88.5%
Total emergy input (U)	1.03×10^{13}	100.0%	2.59×10^{14}	100.0%
Potential environmental input (E_P)	1.61×10^{14}	-	5.93×10^{15}	-

The calculation results of potential environmental input (E_P) are shown in the Table S8.

for local tea. The adoption of all three strategies can reduce the total impact by 74% for exported tea and 63% for local tea.

3.2.4. Sensitivity analysis

The sensitivity analysis of key parameters on the LCIA results of exported tea is shown in Fig. S 2. When the use of coal was varied by ±40%, the CED, GWP, AP, HT, and TT impacts varied between 0.77−1.23, 0.81−1.19, 0.76−1.24, 0.68−1.32, and 0.76−1.24 relative to the baseline result; however, variation in chemical fertilizer application amount and on-field emissions (N_2O and NH_3) has relatively little effects on these impacts. When the emission of NH_3 was varied by ±40%, the EP impact varied by 0.80−1.19 relative to the baseline result; however, variation in the amount of chemical fertilizer and coal has relatively little effects on EP impacts. When the application amount of chemical fertilizer was varied by ±40%, the AT impact varied by 0.96−1.04 times that of the baseline, whereas AT impact was not very sensitive to the variation of the use of coal.

For local tea, when the application amount of chemical fertilizer was varied by ±40%, the CED and HT impacts varied between 0.79−1.20 and 0.78−1.21 relative to the baseline result; however, variation in rapeseed meal application amount and electricity use has relatively little effects on these impacts (Fig. S 3). When on-field emission (N_2O and NH_3) was varied by ±40%, the GWP, AP, and EP impacts varied by 0.79−1.21, 0.74−1.26, and 0.82−1.18 relative to the baseline; whereas the impacts of other parameters were not very great. When the application amount of rapeseed meal was varied by ±40%, the AT and TT impacts varied by 0.93−1.07 and 0.66−1.34 relative to the baseline; however, variation in chemical fertilizer application amount and electricity use has relatively little effects on these impacts.

3.3. Resource use

As shown in Table 10, the total emergy inputs are 1.03×10^{13} sej/kg/year for exported tea and 2.59×10^{14} sej/kg/year for local tea; the latter is 25 times higher than the former. The two tea systems strongly rely on purchased commodity and services, accounting for 96.4–98.0% of total emergy. However, the local resources only account for a small proportion (2.0–3.6%). The nonrenewable emergy flows for exported tea and local tea account for 92.4% and 88.4%, respectively, of total emergy. Clearly, the Chinese tea supply chain is driven by economic feedbacks resources and nonrenewable resources. The potential environmental services reach 1.61×10^{14} sej/kg/year for exported tea and 5.93×10^{15} sej/kg/year for local tea. The emergy of potential environmental services is 15.7 and 23.9 times higher than the total emergy needed for the exported tea and local tea production, suggesting that the emergy required to dilute the environmental emissions from the tea life cycles is far greater than that needed to supply the operation of the tea systems.

Fig. 6 shows the detailed emergy input structure. For exported tea, tea cultivation, primary processing, and refining contribute 43.2%, 47.3%, and 9.5%, respectively, to the entire supply chain. Labor and service account for the highest proportion of 50.1% of the total emergy inputs, mainly resulting from tea cultivation and primary processing. Moreover, coal and chemical fertilizer, also mainly from the two stages, contribute another 18.6% and 17.5%, respectively, to total emergy. For local tea, tea cultivation contributes the highest percentage of 91.6% and the two processing stages contribute only 8.4% to the emergy use. The labor and service, mainly from tea cultivation, contribute the highest (84.1%) to the total emergy use, mainly because local tea is hand-plucked. Moreover, chemical fertilizer accounts for 8.9% of the overall emergy use. The contribution of other inputs is minor.

4. Discussion

4.1. Sustainability of Chinese tea

China is a major tea producer, exporter, and consumer in the world. In this study, we conducted an integrated economic, life-cycle, and emergy analysis, presenting to date the most comprehensive picture of the economic benefits, potential environmental impacts, and the resource use efficiency of tea production in China. Our comprehensive analysis represents a clear step forward compared with previous studies focused only on a single aspect, which may yield misleading or incomplete conclusions. For example, if only profitability is considered, we would favor local tea over exported tea because of its much higher economic profits for tea farmers. But the reality is more complicated, as local tea performs much worse on environmental and emergy indicators. Furthermore, the integration of potential environmental services into emergy analysis represents a methodological advance as this improves upon the classic emergy methods, which ignore the adverse effects of emissions on the environment (Wang et al., 2016). An interesting finding from the emergy analysis is that the potential environmental services are greatly higher than the total emergy driving the two tea supply chains, indicating tea production is a highly polluting industry from the energic perspective.

A major, and surprising, finding of our study is that the GHG emission intensity of China's local tea is much higher than that of exported tea. This high GHG intensity of local tea results mainly from low tea yields, as a result of Chinese consumers' favor of exquisite, tender tea leaves that are harvested in a specific period. Our finding that the environmental impacts of local and exported tea differ substantially has important implications. Had we not separately evaluated the two tea products, we would severely overestimate the environmental footprint of exported tea and thus present misleading results for downstream purchasers in their potential sustainable supply chain management. Similar explorations

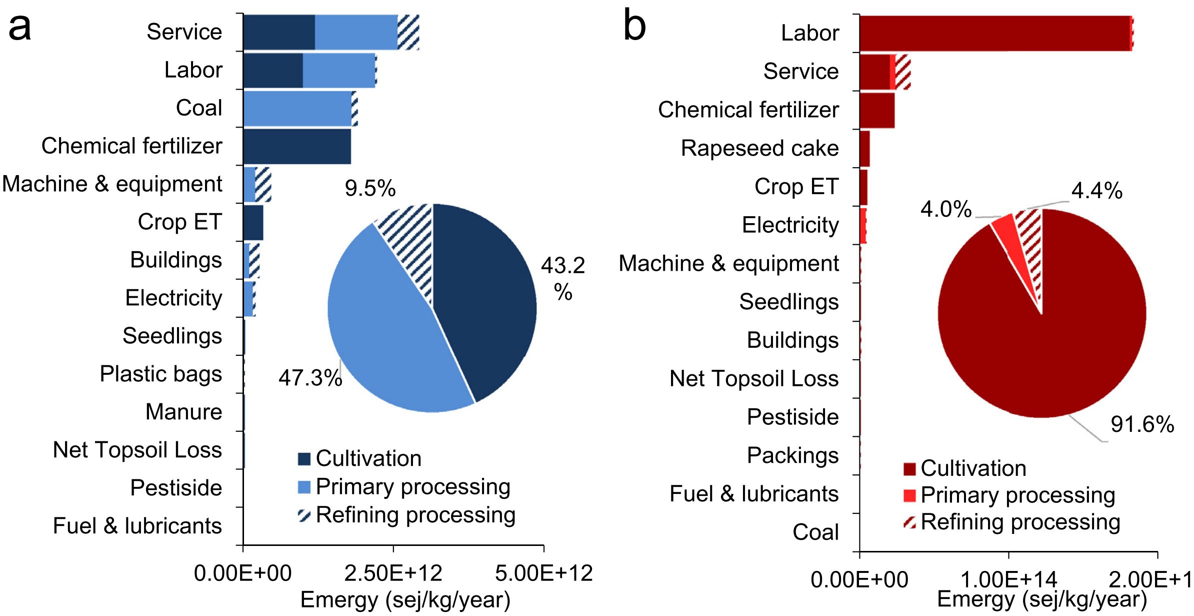

Fig. 6. Emergy input structures of (a) the exported and (b) local tea.

could be carried out for other countries to see if such a difference exists between their locally consumed tea and exported tea. This large difference in China also suggests that if Chinese customers become less finicky about tender tea leaves, e.g., by shifting toward consuming tea bags with tea powder as many international customers do, this could substantially reduce the total environmental impacts of tea production in China.

In conducting the survey and interacting with tea farmers and processes, we have learned several issues related to the sustainability of tea production in China. In the mountainous areas of Southern China, tea cultivation is a pillar industry of economic development, of which profitability is the driving force. The very low profit (0.3 $/kg) of exported tea raises concerns. And it has been caused by a malignant competition among an increasing number of exporting tea companies in China (Wu, 2009). The small profit margin forces the refining factories to lower the purchase price of tea, resulting in upstream primary processing factories and tea farmers bearing the brunt of the costs. Although local tea has a much higher profit, there are also worrying signs. China's local tea requires intensive labor investment, but because of continuous urbanization, labor shortage is an increasing challenge in rural China. This may become an important bottleneck restricting the sustainable development of the China's local tea industry in the near future.

The PAS 2050 classifies emissions > 5 kg CO_2 per kg of product as *highly intensive*.(*The Guide to PAS 2050-2011*). Both local and exported tea in China meet this criterion, highlighting the need to take mitigation measures. First, considering the intensive use of fertilizer in China's tea cultivation, how to achieve sustainable intensification (Tilman et al., 2011; Yang et al., 2018b) may be an important area of focus for future studies. Methods shown to be effective include applying area- and temporal-specific rates of fertilizer (Wu, 2017; Wang et al., 2020) and intercropping of different tea plant species (He et al., 2001). Adopting improved tea cultivars can also reduce the use of fertilizer while increasing yields (Duan et al., 2014). Second, to further reduce the GHG emissions of tea cultivation in China, farmers may use organic fertilizer like manure, which may increase soil carbon stocks (Ji et al., 2018), and switch to renewable energy, including bioenergy. Zhong et al. (2017) showed that biomass granule fuel produced from tea residues amounts to 4800–5000 kcal/kg, which can fully meet the fuel demand in some instant tea processing (Zhong et al., 2017). Finally, the tea industry in China should strengthen the research on the integration of agronomy and agricultural machinery to standardize tea planting and production (Han et al., 2014). The labor efficiency of mechanical plucking is >8 times that of hand plucking and the production cost is 50–70% lower (Mao and Lu, 2006). These strategies can help ensure the long-term environmental and economic sustainability of China's tea industry.

4.2. Limitations

Some limitations are proposed in this study. First, this study analyzes and compares the sustainability of the two most representative Chinese green teas. However, due to the large number of Chinese tea categories, more detailed comparisons are needed in the future, which can provide consumers with more reference for buying tea when they are willing to take responsibility for environmental protection. Second, the average value of the inventory data from different investigated farmers is used for modeling, it should take more into account of the differences between regions due to variable soil and climate types in the future research. Third, the sensitivity analysis indicates that on-field emissions, such as N_2O and NH_3, need to be measured accurately, because variation of these parameters have large impacts on the final results of GWP, AP, and EP.

5. Conclusions

We conducted a comprehensive analysis of the economic benefits, potential environmental impacts, and the resource use efficiency of tea production in China. Although local tea is much more profitable than exported tea, it performs much worse on environmental and energic indicators. These findings provide important information for domestic and international tea beverage companies in their potential sustainable supply chain management of different tea products. The main findings and conclusions are as follows.

Economic analysis showed that local tea has higher economic benefits than exported tea, helping to stimulate the local economic vitality. The costs of labor contributed the most with 43% and 77% to exported and local tea, respectively, at the tea cultivation stage. Export and local tea supply chains are faced with the challenges of low economic benefits and labor shortage, respectively.

Metrics of environmental impacts were yielded, including energy consumption and global warming potential. Based on the assumptions and system boundaries used in this study, local tea resulted in higher yield-scaled potential environmental burdens than exported tea did. Compared with tea refining processing, tea cultivation and primary processing had a greater influence on the environmental impacts. The study found that drying is by far the most energy-consuming and carbon-intensive operation within the exported tea supply chain, mainly due to the use of coal. However, for local tea, fertilization and the resultant on-field emissions were the most energy-consuming and carbon-intensive unit processes, respectively. The life-cycle-based scenario analysis indicates that the environmental impacts of China's local and exported tea can be substantially reduced (by 28–98%) by improving fertilizer use efficiency, adopting new varieties, and using renewable energy.

Total emergy use of local tea is 25 times higher than that of exported tea; thus, the exported tea has a higher production efficiency than local tea does. However, two Chinese tea supply chains were mainly driven by economic imported resources (96.4–98.0%) and nonrenewable resources (88.4–92.4%). Labor and service was the largest single component to the total emergy use of exported (50.1%) and local tea (84.1%), indicating a strong dependence of tea supply chain to labor inputs. The emergy of the potential environmental service required to dilute the environmental emissions from the production process is far more than the emergy needed to supply the operation of the tea production system. Thus, tea production is a highly polluting industry. The exported and local tea industry cannot keep sustainable development in the long run owing to its high environmental burdens. The EMA analysis indicates that the purchasers will benefit greatly from China's tea industry by commodity exchanges; a fairer price of the exported tea should be 51.53 $/kg.

To improve economic vitality and mitigate the environmental and resource use problems of tea production systems, some policy recommendations are proposed. Firstly, improving the mechanization level of tea production can help to enhance labor efficiency. Secondly, promoting substitutions of raw materials and fuels is imperative to strengthen green production of the upstream of tea supply chain. Thirdly, strengthening green and efficient production technology of tea cultivation. Finally, raising the price of exported tea products properly is effective strategies to preserve local nonrenewable resources. This study and its framework of joint use of ECA, LCA, and EMA provide a necessary benchmark to which future system improvements can be compared.

Declaration of Competing Interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.spc.2021.04.019.

References

Azapagic, A., Bore, J., Cheserek, B., Kamunya, S., Elbehri, A., 2016. The global warming potential of production and consumption of Kenyan tea. J. Clean. Prod. doi:10.1016/j.jclepro.2015.07.029.
Bolton, D., 2018. Tea Consumption Second Only to Packaged Water [WWW Document] URL https://worldteanews.com/tea-industry-news-and-features/tea-consumption-second-only-to-packaged-water .
Brown, M.T., Ulgiati, S., 2016. Emergy assessment of global renewable sources. Ecol. Modell. 339, 148–156. doi:10.1016/j.ecolmodel.2016.03.010.
Chen, D., Li, Y., Wang, C., Fu, X., Liu, X., Shen, J., Wang, Y., Xiao, R., Liu, D.L., Wu, J., 2017. Measurement and modeling of nitrous and nitric oxide emissions from a tea field in subtropical central China. Nutr. Cycl. Agroecosyst. 107, 157–173. doi:10.1007/s10705-017-9826-1.
China National Meteorological Information Center [WWW Document], 2020. URL https://data.cma.cn/
, 2019. China Tea Yearbook. China Agriculture Press, Beijing.
Cichorowski, G., Joa, B., Hottenroth, H., Schmidt, M., 2015. Scenario analysis of life cycle greenhouse gas emissions of Darjeeling tea. Int. J. Life Cycle Assess. 20, 426–439. doi:10.1007/s11367-014-0840-0.
Cuadra, M., Rydberg, T., 2006. Emergy evaluation on the production, processing and export of coffee in Nicaragua. Ecol. Modell. 196, 421–433. doi:10.1016/j.ecolmodel.2006.02.010.
DEFRA (Department for Environment, Food and Rural Affairs) and BSI (British Standards Institution). 2011. The guide to PAS 2050:2011: how to carbon footprint your producs, identify hotspots and reduce emissions in your supply chain. London (UK): 79 p.
Doublet, G., Jungbluth, N., 2010. Life cycle assessment of drinking Darjeeling tea - Conventional and organic Darjeeling tea. ETSU Serv., Uster. http://esuservices.ch/fileadmin/download/doublet-2010-LCA-Darjeeling-tea-1.0.pdf.
Duan, X., Tang, Q., Guo, Y., Wang, T., Guo, X., Liu, Hanzhang, Liu, Hong, 2014. Suitability for processing green tea and quality of tea leaves from Zhongcha 108, 302 and 102. Food Sci. 35, 33–37. doi:10.7506/spkx1002-6630-201407007.
Food and Agriculture Organization (FAO). 2019 [WWW Document], n.d. URL http://www.fao.org/faostat/en/#search/tea
GB/T 17296-2009. Classification and codes for Chinese soil., 2009.
Guinée, J.B., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Sleeswijk, Wegener, A., Suh, S., Udo de Haes, a., H., de Bruijn, H., van Duin, R., Huijbregts, M.a.J., Gorrée, M., 2001. Life cycle assessment: an operational guide to the ISO standards art 3: scientific background. Netherlands Minist. Housing, Spat. Plan. Environ. doi:10.1007/BF02978784.
Han, W., Xu, J., Wei, K., Shi, Y., Ma, L., 2013. Estimation of N2O emission from tea garden soils, their adjacent vegetable garden and forest soils in eastern China. Environ. Earth Sci. 70, 2495–2500. doi:10.1007/s12665-013-2292-4.
Han, Y., Xiao, H., Qin, G., Song, Z., Ding, W., Mei, S., 2014. Developing situations of tea plucking machine. Engineering 06, 268–273. doi:10.4236/eng.2014.66031.
He, Z., Yang, X., Baligar, V.C., 2001. Increasing nutrient utilization and crop production in the red soil regions of China. Commun. Soil Sci. Plant Anal. 32, 1251–1263. doi:10.1081/CSS-100104111.
Hill, J., Nelson, E., Tilman, D., Polasky, S., Tiffany, D., 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proc. Natl. Acad. Sci. 103, 11206–11210. doi:10.1073/pnas.0604600103.
Hu, A.H., Chen, C.-H., Huang, L.H., Chung, M.-H., Lan, Y.-C., Chen, Z., 2019. Environmental impact and carbon footprint assessment of taiwanese agricultural products: a case study on Taiwanese Dongshan tea. Energies 12, 138.
Huang, Y, Li, Y, Yao, H., 2014. Nitrate enhances N2O emission more than ammonium in a highly acidic soil. J. Soils Sediments 14, 146–154.
Jefferies, D, Muñoz, I, Hodges, J, King, VJ, Aldaya, M, Ercin, AE, et al., 2012. Water Footprint and Life Cycle Assessment as approaches to assess potential impacts of products on water consumption. Key learning points from pilot studies on tea and margarine. J. Clean. Prod. 33, 155–166.
Ji, L., Wu, Z., You, Z., Yi, X., Ni, K., Guo, S., Ruan, J., 2018. Effects of organic substitution for synthetic N fertilizer on soil bacterial diversity and community composition: A 10-year field trial in a tea plantation. Agric. Ecosyst. Environ. 268, 124–132. doi:10.1016/j.agee.2018.09.008.
Khanali, M., Mobli, H., Hosseinzadeh-Bandbafha, H., 2017. Modeling of yield and environmental impact categories in tea processing units based on artificial neural networks. Environ. Sci. Pollut. Res. 24, 26324–26340.
Kouchaki-Penchah, H., Nabavi-Pelesaraei, A., O'Dwyer, J., Sharifi, M., 2017. Environmental management of tea production using joint of life cycle assessment and data envelopment analysis approaches. Environ. Prog. Sustain. Energy 36, 1116–1122.
Lecumberri, E., Dupertuis, Y.M., Miralbell, R., Pichard, C., 2013. Green tea polyphenol epigallocatechin-3-gallate (EGCG) as adjuvant in cancer therapy. Clin. Nutr. 32, 894–903. doi:10.1016/j.clnu.2013.03.008.
Liang, L., 2009. Environmental impact assessment of circular agriculture based on life cycle assessment: methods and case studies. China Agricultural University.
Luo, S., 2001. Agricultural Ecology. China Agricultural Press, Beijing.
Ma, L., Chen, H., Shan, Y., Jiang, M., Zhang, G., Wu, L., Ruan, J., Lv, J., Shi, Y., Pan, L., Huang, C., Liu, L., Liang, B., Wang, M., Pan, J., 2013. Status and suggestions of tea garden fertilization on main green tea-producing counties in Zhejiang Province. J. Tea Sci. 33, 74–84. doi:10.13305/j.cnki.jts.2013.01.010.
Mao, Z., Lu, D., 2006. Study on mechanized picking of famous tea. China Tea 3, 4–5.
Miller, S.A., Landis, A.E., Theis, T.L., 2006. Use of Monte Carlo analysis to characterize nitrogen fluxes in agroecosystems. Environ. Sci. Technol. 40, 2324–2332. doi:10.1021/es0518878.

Munasinghe, M., Deraniyagala, Y., Dassanayake, N., Karunarathna, H., 2017. Economic, social and environmental impacts and overall sustainability of the tea sector in Sri Lanka. Sustain. Prod. Consum. 12, 155–169.

Nemecek, T., Schnetzer, J., 2011. Methods of assessment of direct field emissions for LCIs of agricultural production systems. Agroscope. Reckenholz-Tanikon Res. Stn..

Odum, H.T., 1983. Systems Ecology: an Introduction. Wiley, New York.

Odum, H.T., 1996. Environmental Accounting: Emergy and Environmental Decision Making. John Wiley and Sons, New York.

Pelvan, E., Özilgen, M., 2017. Assessment of energy and exergy efficiencies and renewability of black tea, instant tea and ice tea production and waste valorization processes. Sustain. Prod. Consum. 12, 59–77. doi:10.1016/j.spc.2017.05.003.

Smith, T.M., Goodkind, A.L., Kim, T., Pelton, R.E.O., Suh, K., Schmitt, J., 2017. Subnational mobility and consumption-based environmental accounting of US corn in animal protein and ethanol supply chains. Proc. Natl. Acad. Sci. 114, E7891–E7899. doi:10.1073/pnas.1703793114.

Soheili-Fard, F., Kouchaki-Penchah, H., Ghasemi Nejad Raini, M., Chen, G., 2018. Cradle to grave environmental-economic analysis of tea life cycle in Iran. J. Clean. Prod. 196, 953–960.

Taulo, J.L., Sebitosi, A.B., 2016. Material and energy flow analysis of the Malawian tea industry. Renew. Sustain. Energy Rev. 56, 1337–1350. doi:10.1016/j.rser.2015.11.072.

The Guide to PAS 2050-2011, How to carbon your product footprint, identify hotspots and reduce your emission in the supply chain, 2011.

Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. 108, 20260–20264. doi:10.1073/pnas.1116437108.

Tokuda, S.I., Hayatsu, M., 2001. Nitrous oxide emission potential of 21 acidic tea field soils in Japan. Soil Sci. Plant. Nutr. 47, 637–642.

van Calker, K.J., Berentsen, P.B.M., de Boer, I.M.J., Giesen, G.W.J., Huirne, R.B.M., 2004. An LP-model to analyse economic and ecological sustainability on Dutch dairy farms: model presentation and application for experimental farm “de Marke. Agric. Syst. 82, 139–160. doi:10.1016/j.agsy.2004.02.001.

Vidanagama, J., Lokupitiya, E., 2018. Energy usage and greenhouse gas emissions associated with tea and rubber manufacturing processes in Sri Lanka. Environ. Dev. 26, 43–54. doi:10.1016/j.envdev.2018.03.006.

Wang, F., Chen, Y., Wu, Z., Jiang, F., Weng, B., You, Z., 2016. Ammonia volatilization and its influencing factors in tea garden soils. J. Agro-Environ. Sci. 35, 808–816. doi:10.11654/jaes.2016.04.027.

Wang, Q., Ma, Z., 2004. Heavy metals in chemical fertilizer and environmental risks. Rural Eco-Environ. 20, 62–64.

Wang, S., Li, T., Zheng, Z., Zhang, X., Chen, H.Y.H., 2019. Soil organic carbon and nutrients associated with aggregate fractions in a chronosequence of tea plantations. Ecol. Indic. 101, 444–452. doi:10.1016/j.ecolind.2019.01.043.

Wang, X., Wu, X., Yan, P., Gao, W., Chen, Y., Sui, P., 2016. Integrated analysis on economic and environmental consequences of livestock husbandry on different scale in China. J. Clean. Prod. 119, 1–12. doi:10.1016/j.jclepro.2016.01.084.

Wang, Z., Geng, Y., Liang, T., 2020. Optimization of reduced chemical fertilizer use in tea gardens based on the assessment of related environmental and economic benefits. Sci. Total Environ. 713, 136439. doi:10.1016/j.scitotenv.2019.136439.

Wu, C., 2009. From tea garden to cup: China’s tea sustainability report. Social Resources Institute, Beijing.

Wu, Y., 2017. Nitrous Oxide emissions and mitigation options in tea field soil. Institute of subtropical agriculture. the Chinese Academy of Sciences.

Xu, Q., Hu, K., Wang, X., Wang, D., Knudsen, M.T., 2019. Carbon footprint and primary energy demand of organic tea in China using a life cycle assessment approach. J. Clean. Prod. 233, 782–792. doi:10.1016/j.jclepro.2019.06.136.

Xu, Y., 2008. Study on the tea farmer organization of shengzhou and its industrial chain forming mechanism. J. Tea 34, 233–236.

Yang, Y., Bae, J., Kim, J., Suh, S., 2012. Replacing gasoline with corn ethanol results in significant environmental problem-shifting. Environ. Sci. Technol. 46, 3671–3678. doi:10.1021/es203641p.

Yang, Y., Tao, M., Suh, S., 2018a. Geographic variability of agriculture requires sector-specific uncertainty characterization. Int. J. Life Cycle Assess. 23, 1581–1589. doi:10.1007/s11367-017-1388-6.

Yang, Y., Tilman, D., Lehman, C., Trost, J.J., 2018b. Sustainable intensification of high-diversity biomass production for optimal biofuel benefits. Nat. Sustain. 1, 686–692. doi:10.1038/s41893-018-0166-1.

Yao, Z., Zheng, X., Liu, C., Wang, R., Xie, B., Butterbach-Bahl, K., 2018. Stand age amplifies greenhouse gas and NO releases following conversion of rice paddy to tea plantations in subtropical China. Agric. For. Meteorol. 248, 386–396. doi:10.1016/j.agrformet.2017.10.020.

Zeng, X., Lu, H., Campbell, D.E., Ren, H., 2013. Integrated emergy and economic evaluation of tea production chains in Anxi. China. Ecol. Eng. 60, 354–362. doi:10.1016/j.ecoleng.2013.09.004.

Zheng, W.-J., Wan, X.-C., Bao, G.-H., 2015. Brick dark tea: a review of the manufacture, chemical constituents and bioconversion of the major chemical components during fermentation. Phytochem. Rev. 14, 499–523. doi:10.1007/s11101-015-9402-8.

Zhong, L., Tang, X., Shao, Z., Wang, X., 2017. Production and application of tea residue biomass granule fuel. Beverage Ind. 20, 50–53.

Zhu, T., Zhang, J., Meng, T., Zhang, Y., Yang, J., Müller, C., et al., 2014. Tea plantation destroys soil retention of NO3− and increases N2O emissions in subtropical China. Soil Biol. Biochem. 73, 106–114.