

Environmental Performance of Soapberry (*Sapindus Mukorossi* Gaertn.) Cultivation in Southeast China based on a Life Cycle Assessment: A Potential Feedstock for Forest-based Biodiesel

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Research Article

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Abstract

Sapindus mukorossi G. has been considered as a potential feedstock for forest-based biodiesel in China. To optimize the cultivation of soapberry and ensure its sustainable supply, an environmental life cycle assessment (LCA) was conducted using a chronological approach combined with extrapolation. Soapberry plantations with two degrees of cultivation intensities were comparatively analyzed. For the studied environmental categories, nitrogen fertilization accounted for half or more of the global warming potential, primary energy demand, acidification and eutrophication potential. The main contributors to ozone depletion were pesticides and potassium fertilizer.

The plantations with a relatively low cultivation intensity presented better environmental performance, mainly due to the lower input of fertilizers, but they are not a priority choice for soapberry cultivation because of low yield. Stakeholders should focus on how to reduce the environmental impacts of the plantations with a relatively high cultivation intensity in this area. Overall, classified management, increasing the yield, reducing the inputs of chemicals and decreasing the unproductive years are the key ways to improve the environmental performance of soapberry cultivation in Southeast China. Woody biomass carbon should be included in LCAs, and 3.71-5.11 t CO₂ can be fixed by soapberry plantations per ha year, indicating that soapberry cultivation provides a net carbon sink.

1. Introduction

According to the Fifth Assessment Report (AR5) from the Intergovernmental Panel on Climate Change (IPCC), more than half of the observed increase in the average global surface temperature from 1951 to 2010 was most likely caused by the anthropogenic increase in greenhouse gas (GHG) concentrations and other human factors [1]. Emissions of CO₂ from fossil fuel combustion and industrial processes contributed approximately 78% of the total increase in GHG emissions from 1970 to 2010 [1]. Because of growing concerns about the environmental impacts of fossil fuel use, the public is increasingly interested in bioenergy. In recent years, forest-based biodiesel has been gaining popularity in developing countries, such as India, China, Malaysia, Indonesia, and Thailand, due to its advantages of low GHG emissions, multiyear harvest and food security [2–6].

Forty-seven species of woody oil plants have been selected by The State Forestry Administration of China (SFA) as potential feedstock for making biodiesel in China [7]. As of 2010, seven species had been planted on a large scale with a total area of 786,630 ha on barren hills and wastelands suitable for afforestation, including *Jatropha curcas* L., *Pistacia chinensis* Bunge, *Sapindus mukorossi* Gaertn., *Sapium sebiferum* (Linn.) Roxb., *Swida wilsoniana* (Wanger.) Sojak, *Vernicia fordii* (Hemsl.) Airy Shaw, and *Xanthoceras sorbifolia* Bunge [4]. However, due to poor cultivars or management practices, high production costs and the lack of market access, unstable feedstock supply is still a major obstacle for the development of forest-based biodiesel [4, 8]. To lower the production cost and improve the affordability of forest-based oil supply, The State Forestry and Grassland Administration of China (SFGA) proposed to develop the forest-based bioenergy “forestry-oil integration” industry, which consists of biodiesel enterprises and combines feedstock forest cultivation with series product manufacturing (such as biodiesel and coproduct production) [8].

Soapberry (*S. mukorossi*) is a multifunctional tree considered to hold particular promise for the development of the forest-based bioenergy “forestry-oil integration” industry in China. It can be used as feedstock for biodiesel and in natural detergents, cosmetics and biomedicine as well as for greening, ecological protection and as a wood supply [9, 10]. Soapberry is a native ornamental landscaping tree that is widely grown in southern China and is planted in temples, courtyards, and parks, on campus and along roadsides. The saponin extracted from the pericarp can serve as an efficient natural surfactant, and the saponin content in the pericarp ranges from 4–27% [11, 12]. The oil content in the kernel is between 26% and 45% [12, 13]. Soapberry oil methyl esters have satisfactory fuel properties and oxidation stability to meet the specific requirements of biodiesel production [14]. Currently, the main soapberry products on the market are soap and detergent, while biodiesel production is still in the research and development (R&D) stage.

Table 1 shows the distribution and area of soapberry plantations in China. Between 2009 and 2020, the area of soapberry plantations had reached 49,184 ha, with more than 95% planted on barren hills/mountains. The area of soapberry plantations in Southeast China accounts for 40.5% of the total area. These plantations are distributed in Fujian, Zhejiang and Jiangxi provinces, all on barren hills, with a planting density of 495–850 trees per ha. According to the degree of cultivation intensity, the soapberry plantations in Southeast China can be divided into three modes: mode 1, mode 2 and mode 3. The cultivation intensity of mode 1 is relatively high, including fertilization twice each year (based on local experience), annual weeding (manual or chemical), pest management and tree pruning (based on local experience). In contrast, mode 2 involves less use of fertilizers (once every 3–4 years), occasional weeding, and no pruning or pest management, representing a relatively low cultivation intensity. Mode 3 includes plantations without any input after planting and with little fruit production.

Table 1
Distribution and area of soapberry plantations in China as of 2020.

Planting area	Province	Area/ha	Former land-use type
Southeast China	Fujian	15580.67	barren hill
	Zhejiang	1000.00	barren hill
	Jiangxi	3333.33	barren hill
Southwest China	Guizhou	24731.33	barren hill
		735.33	farmland
South China	Guangdong	2.33	waste land
		1.53	farmland
Central China	Hunan	3800.00	barren hill

Previous studies on the environmental life cycle assessment (LCA) of forest-based biodiesel have shown that the emissions in the feedstock stage account for a large proportion of the total emissions, such as GHG, SO₂ and NO_x, mainly due to land-use change (LUC) caused by planting of feedstock and the application of chemicals [15–20]. Therefore, this study focuses on the feedstock stage of soapberry biodiesel, and an environmental LCA of soapberry cultivation is conducted.

The goal of this study is to evaluate and compare the environmental performance of soapberry cultivation in two kinds of plantations based on the degree of cultivation intensity in Southeast China using a LCA based on a chronological approach combined with extrapolation. The LCA results can be used as a reference for the selection and optimization of soapberry cultivation methods in Southeast China as well as for providing a database for the LCA of all soapberry products and other products containing soapberry-derived ingredients, such as soapberry biodiesel, soapberry oil and saponins.

2. Materials And Methods

2.1. General State of the Study Area

Data on soapberry cultivation were collected from Jianning County located in northwest Fujian Province, which has the title of “the Town of Soapberry in China”. Jianning County is one of the earliest regions to establish industrial soapberry plantation blocks. In early 2008, large-scale and persistent low temperatures, freezing rain and snowy weather occurred in southern China, which destroyed large areas of Chinese fir plantations in Jianning. Due to its soil and water conservation capacity and high potential values, *S. mukorossi* was chosen by the local government to be planted on the affected hillsides in 2009. As of 2020, there were approximately 5566.7 ha of *S. mukorossi* distributed throughout the county, planted by Yuanhua Forestry Biotechnology Co., Ltd. The areas of mode 1, mode 2 and mode 3 accounted for 25%, 45% and 30%, respectively, of the total area.

2.2. Life Cycle Assessment

According to Standard ISO 14040:2006, an LCA was conducted to evaluate the environmental impacts of soapberry fruit production (and transported to a factory 30 km from the plantation) in two different cultivation modes following the methodological frameworks for perennial crop LCA proposed by Bessou et al. [21]. Two functional units (FUs) were used. The mass-based FU was calculated for the production of 1 ton of dried soapberry fruit over the time boundary. The area-related FU was 1 ha per year of land used to produce soapberry over the time boundary. The time boundary was 20 years.

2.3. Goal and Scope

The goal of LCA was to assess the environmental impacts of soapberry production in two studied cultivation modes in Southeast China. The system boundary was the cradle-to-farm gate, including nursery, seedling transportation, land preparation, unproductive years of the plantations (tree growth without commercial production), productive years of the plantations, fruit harvesting and transportation. All agricultural measures, including fertilization, irrigation, weed mowing, pest control, and pruning, were taken into consideration. Fruit harvesting and transportation referred to the manual harvesting of fruits in the field and their transport to the factory by truck.

2.4. Modeling Approach and Data Collection

The LCA involved six impact categories of soapberry cultivation, namely, global warming potential (GWP), primary energy demand (PED), acidification potential (AP), eutrophication potential (EP), abiotic depletion potential (ADP), and ozone depletion (ODP). All the studied indexes were calculated by eFootprint (<https://www.weblca.net/home>), which is an online software developed by Yi Ke Environmental Technology Co., Ltd., that supports full life cycle process analysis and features a built-in Chinese Life Cycle Database (CLCD) [22]. The CLCD is an industry average database based on the life cycle core model of China's basic industrial system. The CLCD includes inventory data of domestic primary energy, transportation, and basic raw materials [23].

The chronological approach combined with extrapolation was used for modeling in the present study (Fig. 1) [24, 25]. The primary data for nursery and the previous 11 years of soapberry plantations (2009–2019) were collected through company-recorded data and in-field surveys conducted in Fujian and Zhejiang provinces, including planting density, fuel consumption of machinery, fertilizers, herbicides, pesticides, fungicides, yields, and transport distances. Details for different cultivation modes are described in Sect. 2.4.1. For the subsequent 9 productive years of the soapberry crop, data of chemical inputs and yields were extrapolated based on the data of the last five years (years 7–11). The secondary data were obtained from the CLCD 0.8.1 and Ecoinvent 3.1.0 databases.

Among them, data of fertilizer production, diesel combustion, energy consumption of transportation and land preparation were obtained from the CLCD 0.8.1 database. Data of herbicides and pesticides were obtained from the Ecoinvent 3.1.0 database.

2.4.1. Soapberry Cultivation Modes

The studied soapberry cultivation modes are described in the following paragraphs. Seedlings were two years old and came from a nursery in Tiantai County, Zhejiang Province (a province in southeast China, adjacent to northern Fujian), operated by Tiantai County Manyuanchun Agricultural and Forestry Development Co., Ltd. The characteristics and inputs of the nursery are shown in Table 2. The key agronomic data of soapberry plantations are listed in Table 3.

Table 2
Main characteristics of the nursery and the major inputs.

Characteristics	Mode 1	Mode 2
Density of seedlings (number of trees/ha)	150,000	
Years of cultivation	2	
Irrigation system	No irrigation	
Seedlings transportation (km)	650	
Inputs	Year 1	Year 2
N (kg/ha)	666.6	666.6
P ₂ O ₅ (kg/ha)	858.4	333.4
K ₂ O (kg/ha)	500	500
urea (kg/ha)	225	750

Table 3
Key agronomic data of soapberry plantations with the 20-year time range in Jianning, China.

Mode 1	Units	Unproductive years		Productive years										
		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12- (high yield)	
<i>Fertilizers</i>														
N	kg/ha	79.294	59.471	79.294	99.118	148.676	198.235	247.794	99.118	247.794	346.912	346.912	257	
P ₂ O ₅	kg/ha	19.824	29.735	39.647	49.559	74.338	99.118	123.897	49.559	123.897	173.456	173.456	128	
K ₂ O	kg/ha	19.824	44.603	59.471	74.338	111.507	148.676	185.846	74.338	185.846	260.184	260.184	193	
Organic fertilizer	kg/ha	0	0	0	991.176	0	0	0	991.176	0	0	0	198	
<i>Herbicides</i>														
Glyphosate	kg/ha	0	0	0	0.675	0.675	0	0	0.45	0.45	0.36	0.45	0.34	
Butachlor	kg/ha	0	0	0	0	0	0	0	0.5625	0	0	0	0.11	
Total herbicides	kg/ha	0	0	0	0.675	0.675	0	0	1.0125	0.45	0.36	0.45	0.45	
<i>Pesticides</i>														
Imidacloprid	kg/ha	0	0	0	0	0.135	0.045	0.068	0.18	0.18	0.09	0.18	0.14	
Abamectin	kg/ha	0	0	0	0	0	0.00012	0.00012	0.00012	0.00012	0	0	0.00	
Emamectin benzoate	kg/ha	0	0	0	0	0	0	0	0.0074	0	0	0	0.00	
Cyhalothrin	kg/ha	0	0	0	0	0	0	0.0025	0.006	0.0011	0	0	0.00	
Chlorpyrifos-ethyl	kg/ha	0	0	0	0	4.35	1.45	1.88	4.35	4.35	4.35	4.35	3.85	
Acetamiprid	kg/ha	0	0	0	0	0.2	0.2	0.2	0	0.399	0	0	0.12	
Thiamethoxam	kg/ha	0	0	0	0	0	0	0	0	0	0.03	0.03	0.01	
<i>Bacillus thuringiensis</i>	kg/ha	0	0	0	0	0	0	0	0.0088	0	0	0	0.00	
Total pesticides	kg/ha	0	0	0	0	4.685	1.69512	2.15062	4.55232	4.93022	4.47	4.56	4.13	
Yield	t/ha	0	0	0.147	1.059	0.824	2.588	2.971	2.088	1.500	0.824	2.228	2.97	
<i>Mode 2</i>														
	Units	Unproductive years			Productive years									
		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12- (high yield)	
<i>Fertilizers</i>														
N	kg/ha	78.834	59.125	0	0	147.814	0	0	0	0	344.898	0	68.9	
P ₂ O ₅	kg/ha	19.708	29.563	0	0	73.907	0	0	0	0	172.449	0	34.4	
K ₂ O	kg/ha	19.708	44.344	0	0	110.860	0	0	0	0	258.674	0	51.7	
<i>Herbicides</i>														
Glyphosate	kg/ha	0	0	0	0	0	0	0.675	0.6	0	0	0.6	0.37	
Yield	t/ha	0	0	0	0.165	0.530	0.792	1.199	0.877	0.809	0.432	0.743	1.19	

2.4.1.1. Mode 1

Land preparation involved removal of the previous vegetation, soil preparation and digging based on company standards. For land preparation, the level steps were applied to avoid water and soil erosion. The size of planting holes was 50 cm × 40 cm × 40 cm, and the plantation tasks were performed manually with a planting density of 495 plants per ha. The headed truck height of seedlings was set at 0.5 m. After plantation establishment in 2009, fertilizers were applied

artificially twice per year, and the amount increased annually. In 2012 and 2016, some of the chemical fertilizers were replaced by organic fertilizer. During the nonproductive years after planting (2009–2010), no herbicides or pesticides were applied, and only manual weeding was conducted twice per year from May to August. With plantation growth, weed and pest control were important during the early productive stage. Based on the field survey, weeds in soapberry plantations mainly belonged to the Compositae, Gramineae and Rosaceae families. Between 2012 and 2013 and between 2016 and 2018, glyphosate was applied 2–3 times per year according to the instructions. Eight pesticides were mainly applied to prevent and eliminate moths, aphids and inchworms. Detail data of the plantations are listed in Table 3. All agrochemicals were applied using manual backpack sprayers. Irrigation was not required, and water use took place only for field input dilution. Branch pruning based on the experience of local farmers was conducted manually once a year. The residue of pruning was collected by farmers for firewood. The plantation was cleared each year after fruit harvest. The average yield between 2011 and 2019 was $1.53 \text{ t ha}^{-1} \text{ yr}^{-1}$. Fruit harvesting was carried out manually using a ladder and bamboo pole in late November, and fruits were air dried.

2.4.1.2. Mode 2

There was no land preparation by machinery for mode 2. Trees were planted on the hillside after manual clearing of shrubs and grass, with a density of 833 plants per ha. The setting of the headed truck height of seedlings was the same as in mode 1. Afterwards, artificial pruning was performed only once. Intermittent fertilization and weeding were applied during the 11 years (Table 3). No pesticides were applied. The unproductive phase lasted for 3 years after plantation establishment. Detail data from 2009 to 2019 of the plantations are listed in Table 3. The average yield between 2012 and 2019 was $0.69 \text{ t ha}^{-1} \text{ yr}^{-1}$.

2.5. Field Emissions

N sources from synthetic N fertilizer (F_{SN}) and organic N (F_{ON}) applied were included in the calculation of direct N_2O emissions. The emission factor (EF_1) for N_2O -N emissions was 1% of the applied N amount [26], as local experimental data were lacking. Indirect N_2O emissions include two pathways. The first is the volatilization of N as NH_3 and oxides of N (NO_x) and the deposition of these gases and their products, NH_4^+ and NO_3^- , onto soils and the surface of lakes and other waters. The second pathway is the leaching and runoff from land of N from synthetic and organic fertilizer additions. In the present study, N_2O emissions from atmospheric deposition of N volatilized from managed soil were estimated using Eq. 1, and the N_2O emissions from leaching and runoff were estimated using Eq. 2 [26]. NO_x -N and NH_3 -N were calculated based on IPCC data [26].

$$\text{N}_2\text{O}_{(ATD)}\text{-N} = [(F_{SN} \times \text{Fra}_{\text{GASF}}) + (F_{ON} \times \text{Fra}_{\text{GASM}})] \times EF_2 \quad (1)$$

$$\text{N}_2\text{O}_{(L)}\text{-N} = (F_{SN} + F_{ON}) \times \text{Fra}_{\text{LEACH-(H)}} \times EF_3 \quad (2)$$

With

$\text{N}_2\text{O}_{(ATD)}\text{-N}$ = amount of N_2O -N produced from atmospheric deposition of N volatilized from soil (kg ha^{-1})

$\text{N}_2\text{O}_{(L)}\text{-N}$ = amount of N_2O -N produced from leaching and runoff of N additions to soil, (kg ha^{-1})

F_{SN} = amount of synthetic fertilizer N applied to soils (kg ha^{-1})

F_{ON} = amount of organic fertilizer N applied to soils (kg ha^{-1})

Fra_{GASF} = fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_x (10%), $\text{kg N volatilized (kg of N applied)}^{-1}$

Fra_{GASM} = fraction of organic fertilizer N that volatilizes as NH_3 and NO_x (20%), $\text{kg N volatilized (kg of N applied)}^{-1}$

$\text{Fra}_{\text{LEACH-(H)}}$ = fraction of all N added to/mineralized in soils in regions where leaching/runoff occurs that is lost through leaching and runoff (30%), $\text{kg N (kg of N additions)}^{-1}$

EF_2 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces (1%), [$\text{kg N}_2\text{O-N (kg NH}_3\text{-N + NO}_x\text{-N volatilized)}^{-1}$]

EF_3 = emission factor for N_2O emissions from N leaching and runoff (0.75%), $\text{kg N}_2\text{O-N (kg N leached and runoff)}^{-1}$

CO_2 -C emission from urea fertilization in the nursery was obtained by multiplying the amount of urea fertilization by the emission factor ($EF_4 = 20\%$) [26]. N loss through leaching and runoff was calculated as 30% of the fertilizer N applied [26], and P loss was calculated as 0.2% of the fertilizer P applied [27]. The emissions of pesticide losses to freshwater, soil and air were determined using a standard residue rate of 1%, 43% and 10% per unit weight of pesticide active ingredients applied, respectively [28].

2.6. Woody Biomass Carbon (C)

Biogenic CO_2 fixation of soapberry trees was taken into account and included in the LCA, as the fixed C of trees is preserved [8, 29]. The annual woody biomass increment of soapberry plantation was obtained from Liu et al. [8]. The carbon contents of the stem, branch and root were determined with a FLASH 2000 CHNS/O elemental analyzer (Thermo, USA). Ultimately, the biomass C was obtained by multiplying the woody biomass by the average carbon content.

2.7. Data Assumptions

2.7.1. Yield Estimation

In the present study, a range of yield from year 12 to year 20 was predicted to accommodate the considerable variability of soapberry production. Since both the yields of mode 1 and mode 2 had reached a peak in year 7, i.e., 2.97 and 1.20 t ha⁻¹, respectively, it was assumed that the annual maximum yield in the later nine years was equal to the yield in year 7, and the minimum yield was the same as the lowest production during years 7–11 (Table 3). In addition, the average yield of years 7–11 was taken as the average yield of the later nine years. Therefore, the accumulated yield over 20 years of mode 1 and mode 2 was 21.64–40.96 t ha⁻¹ and 9.44–16.34 t ha⁻¹, respectively.

2.7.2. Changes in Soil Carbon (C) Caused by LUC

The change in soil C caused by LUC was not taken into account due to the lack of data. As soapberry plantations were established on barren hillsides (no perennial trees or shrubs), it was considered that the C debt caused by LUC was zero in the present study.

2.7.3. Transportation

It was assumed that the vehicle used to transport seedlings was a heavy-duty truck with a 10-t load, and the distance covered was 650 km. A pick-up truck with a capacity of 2 t was used to transport fertilizers and fruits, and the transport distances for fertilizers and fruits were 15 km and 30 km, respectively. The transportation of agrochemicals was not considered in this study.

2.7.4. Residues

The destruction or burning of residues during land preparation and the resulting CO₂ emissions were not considered. The emissions produced by pruning residues and litter were not taken into consideration.

2.7.5. N Sequestration

The N sequestered in trees was not accounted for in this study.

3. Results

3.1. Environmental Impacts of the Two Cultivation Modes

Figure 2 shows comparative results from the LCA of all assessed impact categories in the two studied cultivation modes with different yield levels without considering the biogenic CO₂ fixation. At the same yield level, mode 2 produces values 28.45–40.74% lower than those of mode 1 for GWP, PED, AP, EP and ADP per ton of fruit, and 80.63–83.21% lower than mode 1 for ODP; the impact per (ha year) of mode 2 for the studied impact categories was 71.46–74.16% lower than that of mode 1. As seen in Fig. 2, the yield has a significant influence on all the studied impact categories per ton of fruit. In mode 1, when the yield increases by 45.69% (from 1.08 to 1.58 t ha⁻¹ year⁻¹) and 89.3% (from 1.08 to 2.05 t ha⁻¹ year⁻¹), the impact values decrease by 30.98–31.35% and 46.47–47.15%, respectively. Similarly, the impact values decrease by 23.79–26.58% and 38.24–42.21% as the yield increases by 36.23% (from 0.47 to 0.64 t ha⁻¹ year⁻¹) and 73.14% (from 0.47 to 0.82 t ha⁻¹ year⁻¹) in mode 2, respectively.

According to the carbon content of soapberry (Table 4) and the annual woody biomass increment of soapberry plantations in Jianning County [8], the average CO₂ sequestration of soapberry plantations is 5.65 t (ha year)⁻¹. Subtracting the emissions from the cultivation process, 3.71–5.11 t CO₂ can be fixed by soapberry plantations per ha year (Fig. 3a). If woody biomass C stock is taken into account for the calculation of GWP, the CO₂ absorbed by trees can completely offset the CO₂eq emissions during the cultivation period. Soapberry cultivation represents a carbon sink, and the amount of CO₂ sequestration in the life cycle of mode 1 and mode 2 is 1.81–3.44 t CO₂eq and 6.25–10.83 t CO₂eq per ton of fruit (Fig. 3b), respectively.

Table 4
Carbon contents in different organs of soapberry.

Item	Stem	Branch	Root (≥3 cm)	Root (1–3 cm)	Root (0.2–1 cm)	Root (≤0.2 cm)	Wood
Carbon content/%	46.78 ± 0.912	46.94 ± 1.209	43.69 ± 1.587	45.68 ± 3.984	45.62 ± 6.978	46.57 ± 6.114	46.39 ± 0.099

3.2. Contributions of Agricultural Stages to the Studied Environmental Impacts

Figures 4 and 5 present the relative contribution of each stage to the six calculated environmental categories under the two cultivation modes with average yield (mass-based FU). The productive stage contributes 88.58–96.06% and 81.28–90.86% to the studied impact categories in mode 1 and mode 2, respectively. In mode 1, N fertilizer contributes most to GWP (75.92%), PED (52.03%), AP (75.70%) and EP (91.65%); P fertilizer contributes most to ADP (44.44%); while weed and pest control contributes most to ODP (70.17%). In mode 2, the main contributors to GWP, PED, AP, EP and ADP are the same as in mode 1, but K fertilizer contributes most to ODP. The contribution of fruit harvest and transportation to most impact categories is only approximately 2% owing to the short distance between the plantations and the factory.

In addition, the unproductive stage in mode 2 contributes 9.14–18.72% to all impact categories, which is higher than that of mode 1 (3.94–11.42%). Two reasons are mainly responsible for this result: one is that the unproductive period of mode 2 is longer than that of mode 1, and the other is that the chemical inputs in the productive stage of mode 2 are lower than those in mode 1. In mode 1, the main contributor to GWP, PED, AP, ADP and ODP is land preparation, while unproductive years of the plantations contributes most to EP, mostly due to fertilization. In mode 2, the main contributor to ODP is nursery & seedling transportation, and the main contributor to the other impact categories is the unproductive years of the plantations.

4. Discussion

4.1. The Impact of Yield and Fertilization on the LCA Results

Based on the LCA results, yield is one of the key factors affecting the environmental performance of soapberry cultivation. The estimation of yield from year 12 to year 20 can determine which of the two modes has less of an impact on the environment. As Fig. 2 indicates, at the low yield level, the impact per ton of fruit in mode 1 presents a 52.85-495.60% higher value than that in mode 2 for all impact categories. However, the impact per ton of fruit in mode 1 with high yield is 10.49-19.23% lower than that in mode 2 with low yield for GWP, PED, AP, EP and ADP. This phenomenon is consistent with the results of previous studies on other biodiesel feedstocks. As the seed yield is enhanced, the carbon balance of jatropha oil and jatropha biodiesel in China is improved [30]. In arid and semi-arid lands, the seed yield of *Jatropha curcas* needs to reach 8.6 – 13.9 t hm⁻² year⁻¹ to repay the C debt caused by the transformation from shrub to jatropha plantations in 30 years [31], but the current seed yield of *Jatropha curcas* is far from that [30, 32, 33]. Therefore, increasing the yield of fruits (or seeds) is of vital importance for forest-biodiesel feedstocks. According to a field survey, the yield of soapberry clonal plantations in Jianning County is 1.00, 1.91 and 2.72 t ha⁻¹ in the 4th, 5th and 6th year after grafting, respectively. Compared with the yield data in Table 3, the fruit yield of clonal plantations in the sixth year after grafting is 2.6-fold of that of seedling plantations in the same year, but the amount of chemicals inputs is the same. At present, the soapberry clonal plantation area is only 3.3 ha and these plantations were only built 4 years ago; therefore, there is not enough yield data, but the advantages of clonal plantations in terms of yield are evident.

The higher environmental impact observed for most impact categories in the studied modes is mainly related to fertilization in the productive stage, especially nitrogen application. As Figs. 4 and 5 indicate, fertilization, including production, transportation and in-field emissions, contributes 81.19-95.66% to GWP, PED, AP, EP and ADP in mode 1 and 59.76-88.47% to all studied impact categories in mode 2. For GWP, the main source was N₂O emissions from N fertilizers applied to the plantation in the productive stage, which contributed 56.82% (mode 1) and 55.05% (mode 2) of the total GHG emissions, followed by GHG emissions from fertilizer production. For most biofuel pathways, GHG emissions caused by fertilization account for a large proportion during both the feedstock stage and the whole life cycle of biofuels [18, 34-36]. Therefore, fertilization is also a crucial factor affecting the environmental performance of biofuels. The sensitivity analysis was performed as the % variation per impact category with organic fertilizer replacing 50% of chemical fertilizers in the productive stage of soapberry cultivation in comparison to the base cases, without considering biogenic CO₂ fixation (Fig. 6). The use of organic fertilizer in productive years of plantations reduces GWP by 45% and 43%, PED by 43% and 41%, AP by 39% and 44%, EP by 45 and 44%, ADP by 43% and 44% and ODP by 11% and 30% for mode 1 and mode 2, respectively. ODP is affected not only by fertilization but also by pesticides in mode 1, so the reduction rate in mode 1 is less than that in mode 2.

4.2. GHG Balance

For soapberry cultivation, the GHG balance is determined jointly by CO₂ fixed by tree growth and GHG emissions from agricultural management. The amount of fixed CO₂ in soapberry plantations is 5.65 t (ha year)⁻¹ and 3.71-5.11 t CO_{2eq} can be stored per ha year by subtracting the emissions. Compared with *Jatropha* plantations in China [33], these plantations can absorb more GHG per ha during the feedstock stage. According to section 2.1, the areas of mode 1 and mode 2 are 1391.7 ha and 2505.0 ha, respectively, in Jianning. With the 20-year time boundary, the total CO_{2eq} stock is 1.03 × 10⁵ t and 2.56 × 10⁵ t for mode 1 and mode 2, respectively.

As the yield increases, the amount of CO₂ absorbed by soapberry plantations allocated to produce per ton of fruit decreases. However, with constant chemical inputs, GHG emissions from producing 1 t of fruits would also decrease as the yield increases. However, what happens to the GHG balance of soapberry cultivation? Fig. 7 presents the net CO_{2eq} stock of soapberry cultivation in the life cycle by changing the yield of fruit per hectare of 20 years in mode 1 and mode 2. The net CO_{2eq} stock decreases as the yield increases and is infinitely close to but greater than zero in the two modes. That is, the soapberry cultivation process is a net carbon sink. For example, when the yield increases by 0.5-, 1- and 2-fold based on the average yield, the net CO₂ stock of mode 1 is 1.57, 1.17 and 0.78 t and that of mode 2 is 5.30, 3.97 and 2.64, respectively.

4.3. Recommendations on Soapberry Plantations in Southeast China

Based on the results, we can conclude that mode 1 (plantations with a relatively high cultivation intensity) in Southeast China is less environmentally sustainable than mode 2 (plantations with a relatively low cultivation intensity) since the chemical inputs (especially fertilizer) during the cultivation process in mode 1 are much higher. However, mode 2 is not the preferred mode for soapberry cultivation because of its low yield. Therefore, it is of great significance to conduct classified management and directional cultivation of soapberry plantations to increase yield and reduce cultivation costs and environmental impacts.

For plantations over 10 years old (plantations in the period of stable fruit production based on local experience) in mode 1 and mode 2, reasonable thinning, stable fertilization and pest control should be conducted to prolong the lifespan of the plantations and ensure a stable yield. For the remaining plantations in mode 1, more efforts should be focused on increasing yield and reducing the use of chemical fertilizers. It is essential for stakeholders to implement other kinds of fertilizers (e.g., slow-release fertilizers, organic fertilizers or green manure) instead of NPK fertilization to reduce the environmental impacts [36, 37]. Increasing the frequency of fertilization and reducing the amount of fertilizer used in each application can improve fertilizer use efficiency and reduce N₂O emissions from applied N fertilizer. At the same time, a reasonable fertilization strategy based on the growth stages of soapberry tree (appropriate N application rate, formulation, timing of application and placement) should be studied [38, 39]. Furthermore, stakeholders should pay attention to recent technology research to increase the yield of soapberry. For example, soapberry trees with three backbone branches, a 60° opening angle and with 16-18 fruiting branches per m² crown projection area could most effectively improve the yield by one- or two-fold [40]. Spraying 3% sucrose 3 times (with an interval of 7 days) before the physiological fruit-dropping period could increase the yield by 3- to 5-fold, and auxiliary pollination by bees with 3 beehives per hectare

could increase the yield by 1.2-fold [8, 39]. For unmanaged plantations and other plantations in mode 2, the cultivation purpose should be changed to ecological forests to reduce costs and carbon sink increases. For the future construction of raw material plantations, clonal plantations should be given priority to shorten the juvenile phase and maintain a stable yield as it can effectively increase the yield of soapberry, as discussed in section 4.1.

5. Conclusions

Based on the LCA results, the plantations with a relatively low cultivation intensity have better environmental performance in Southeast China, but they are not preferred due to their low yield. As a potential feedstock for biodiesel in China, soapberry cultivation needs to be further improved from an environmental perspective, particularly in relation to fertilization in the plantations with a relatively high cultivation intensity, which contributed most to GWP, PED, AP, EP and ADP. Classified management and directional cultivation of soapberry plantations are proposed. In addition, woody biomass C stock has a significant impact on GWP for soapberry production and should be considered in LCAs. This work contributes to soapberry LCA in Southeast China and provides an upstream database for LCAs of several products containing soapberry-derived ingredients.

Declarations

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

Availability of Data and Material

Data directly supporting the study results can be found at the authors.

Code Availability

Not applicable.

Author Contributions

Conceptualization, S.L. and L.J.; data curation, S.L. and J.L.; formal analysis, S.L. and J.L.; investigation, S.L., J.L., Y.G., S.G. and G.Z.; methodology, S.L., J.L., Y.G., B.X., Z.C., and S.C.; project administration, L.J.; resources, X.W.; supervision, L.J.; writing—original draft, S.L.; writing—review and editing, S.L., J.L., B.X., Z.C., S.C. and L.J.; All authors have read and agreed to the published version of the manuscript.

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Figures

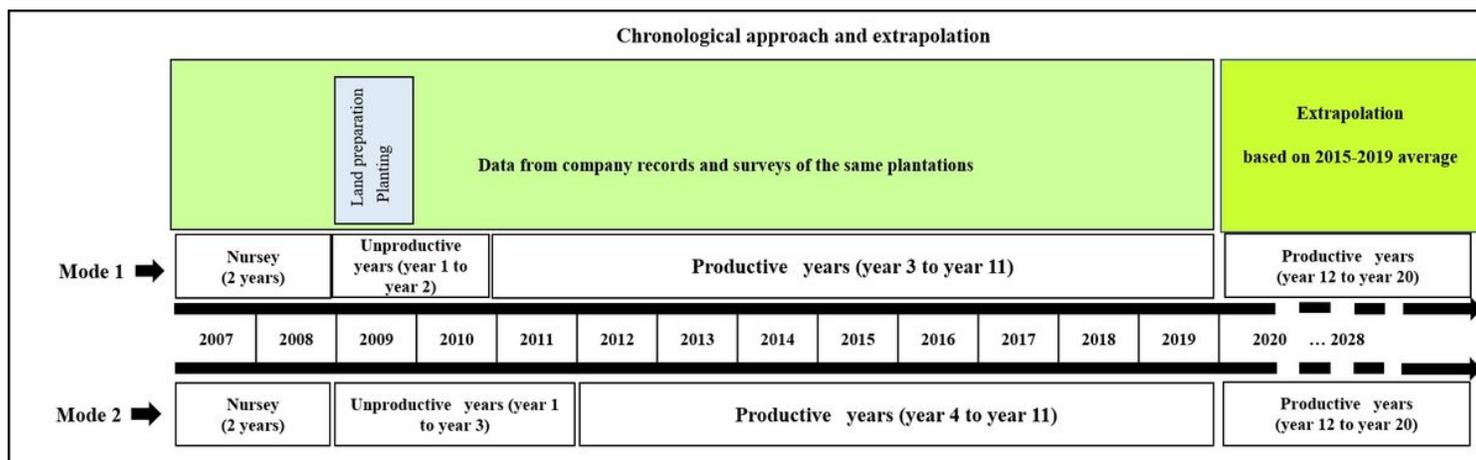


Figure 1

Representation of the two studied modes

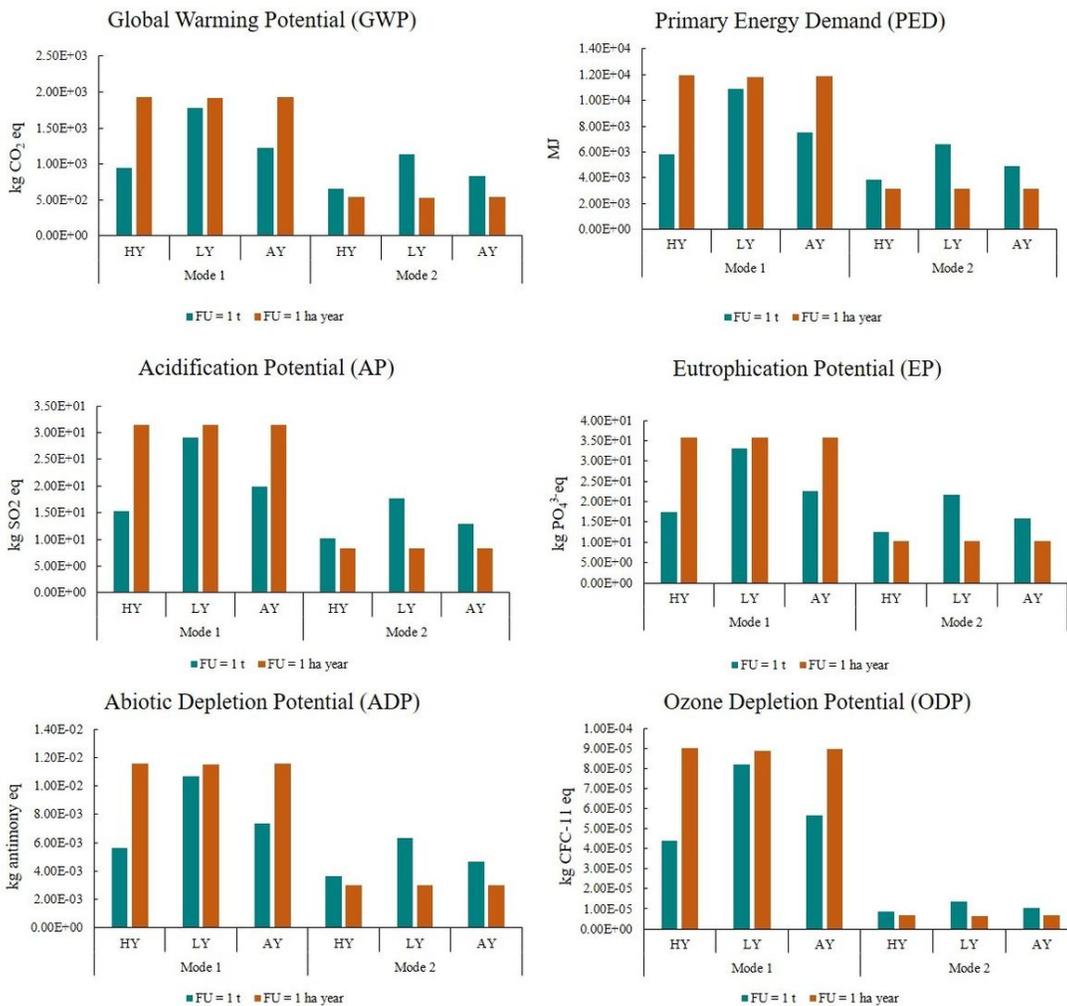


Figure 2
Comparative results of the life cycle environmental impacts of soapberry in mode 1 and mode 2 with different yield levels (biomass C is not considered). HY: high yield; LY: low yield; AY: average yield

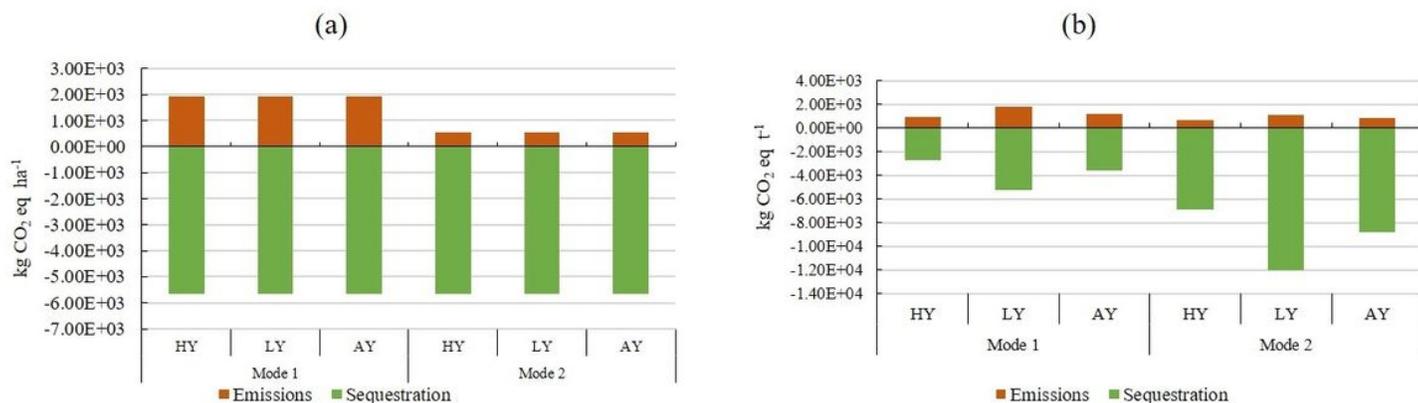


Figure 3
Life cycle CO₂ accounting based on per ha of land use (a) and per ton of fruit (b). HY: high yield; LY: low yield; AY: average yield

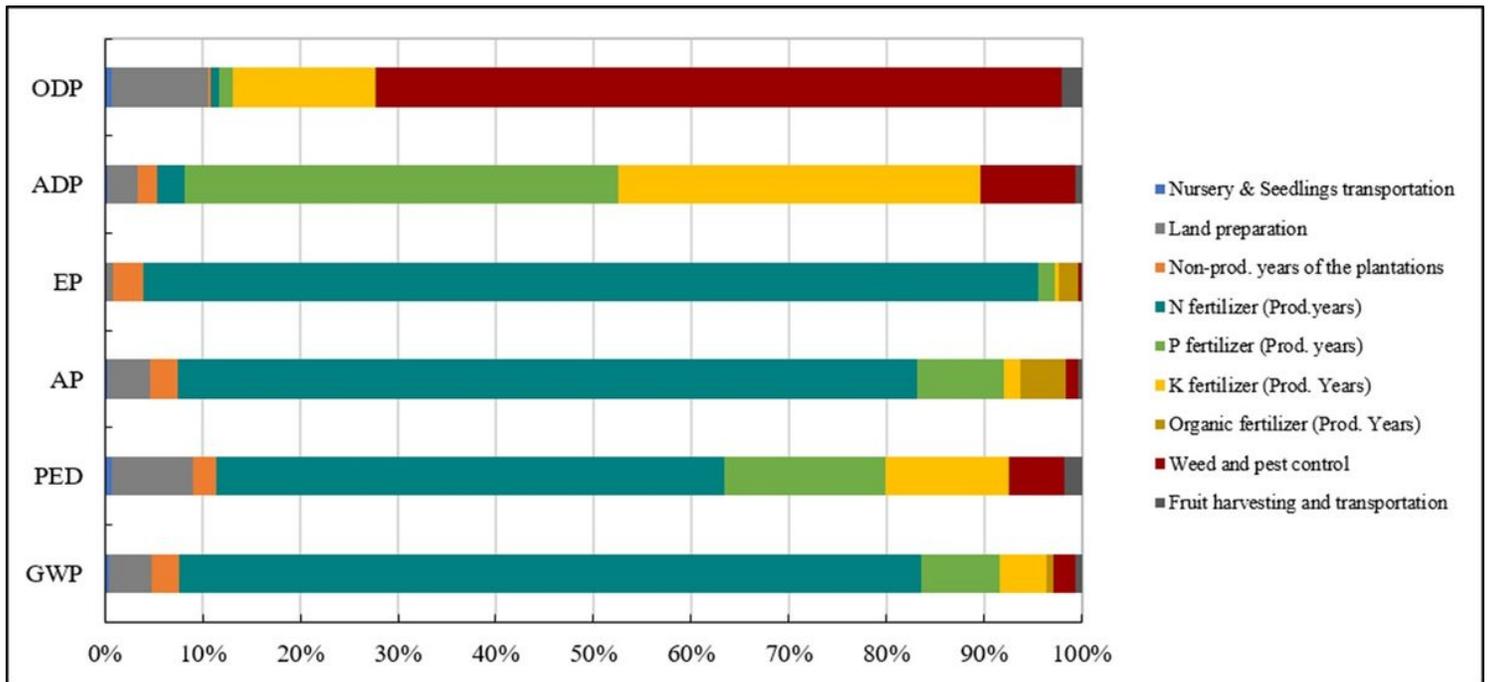


Figure 4

Contributions of different stages to the total scores within each environmental impact category in mode 1-average yield

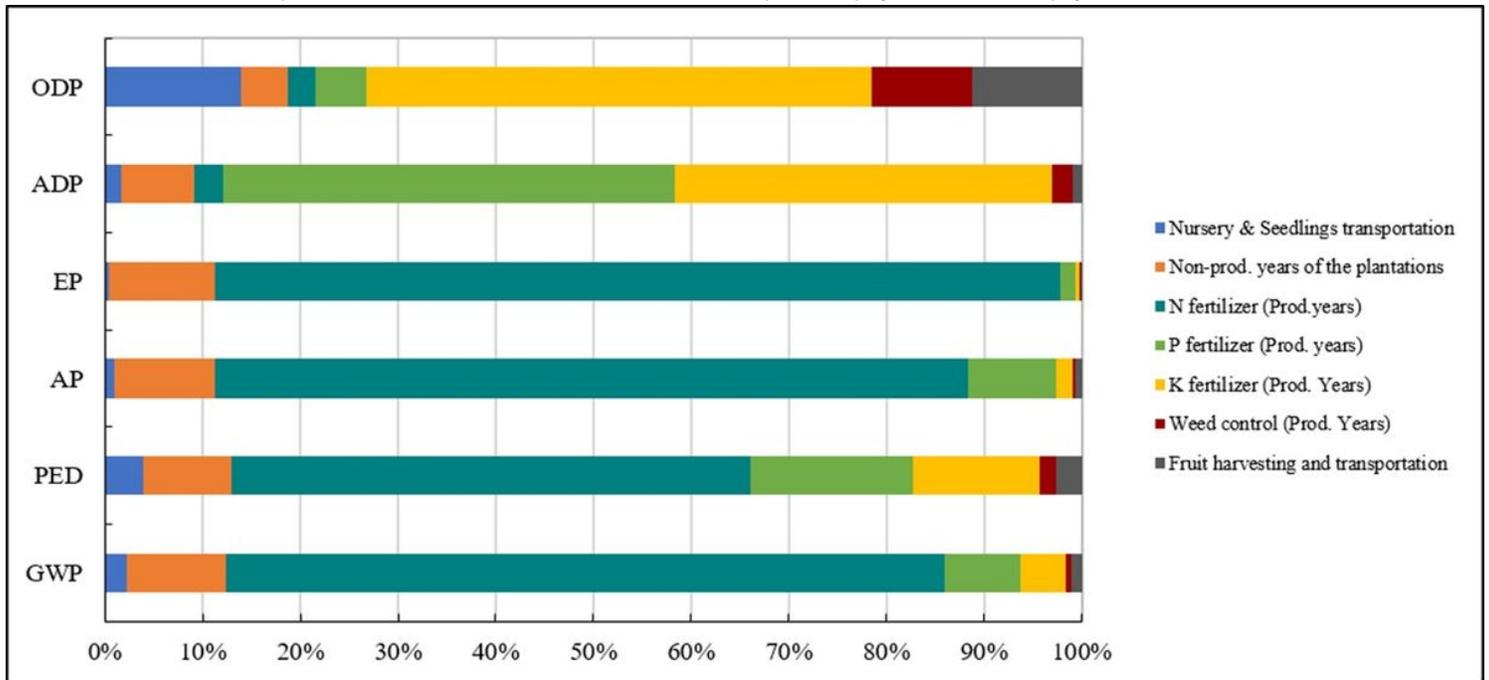


Figure 5

Contributions of different stages to the total scores within each environmental impact category in mode 2-average yield

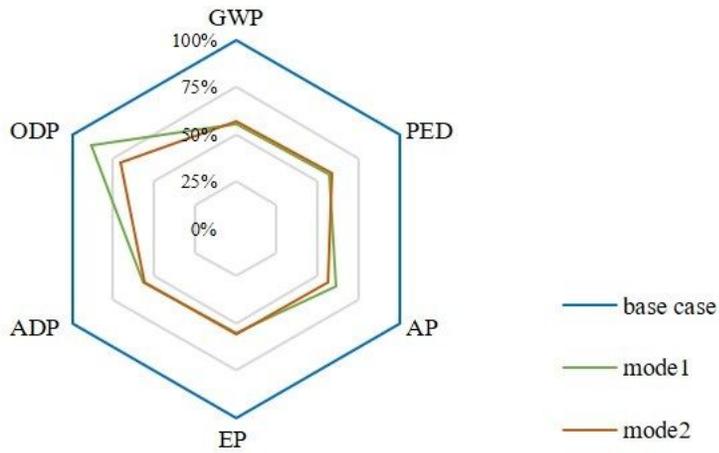


Figure 6
 Percentage variation of the impact categories with organic fertilizer replacing 50% of the chemical fertilizers

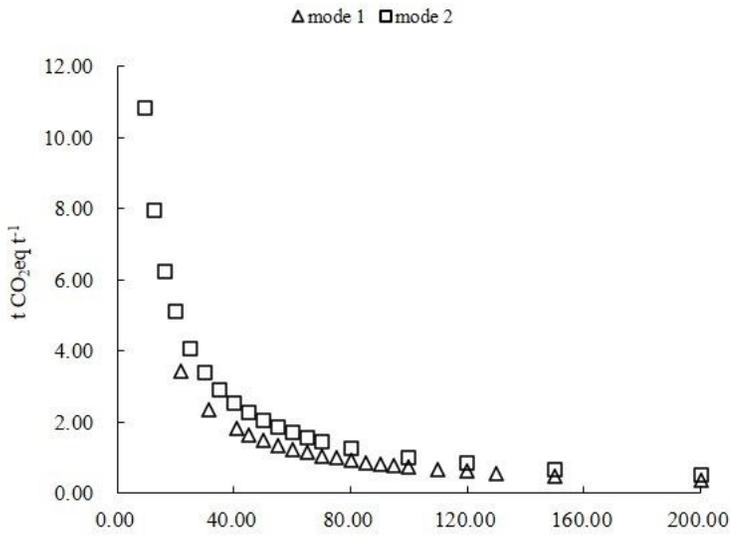


Figure 7
 Evolution of CO₂ stock of soapberry cultivation process in mode 1 and mode 2 as a function of yield (per ton of soapberry fruit)