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Original article

Study on life-cycle carbon emission accounting of cane sugar products based on ammonia-based CO_2 capture method

Lixiao Luo [a,1], Wei Zhang [b,1], Yu Zhang [b,*], Dongdong Feng [b], Yuzhi Li [b], Xishan Zhu [a], Haibo Ye [a], Weichong Chen [a], Yingsen Qin [a]

[a] Guangxi Special Equipment Inspection and Research Institute, Nanning 530299, China
[b] School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

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ABSTRACT

China's cane sugar whole life cycle carbon accounting remains blank, which is urgent to formulate an emission reduction strategy. A life-cycle carbon accounting model for cane sugar products is established, with the carbon emission accounting conducted for planting, harvesting, transportation, processing, waste treatment, packaging, and other aspects of the cane sugar industry, which is multi-temporal and multi-scale. The quantitative and systematic assessment of carbon emissions from the cane sugar industry is accomplished. A new ammonia-based CO_2 capture method has been innovatively proposed to achieve harmful carbon emission reduction from sugar products using sugar flue gas. The results show that the construction of the cane sugar life-cycle carbon accounting model can more accurately describe the comprehensive carbon footprint of the Chinese sugar industry. The carbon footprint of sucrose is −1.4259 CO_2e/kg sugar, of which the highest carbon emission from agricultural fertilizers is 46.9 %. The new ammonia-based CO_2 capture method enables 0.1319 t/t sugar of nitrogen fertilizer while achieving an overall reduction of 29 % in carbon emissions from sucrose, significantly reducing carbon emissions from agriculture. Its carbon footprint of cane sugar is greatly degraded to −2.1494 CO_2e/kg sugar. The research provides a scientific basis for developing a carbon emission assessment for sugar while demonstrating that cane sugar has a sizeable carbon-negative potential in the future.

Introduction

Carbon emissions have garnered widespread attention in the international community, leading to a strong consensus among countries reducing CO_2 emissions [1]. The Chinese government has announced a precise series of carbon emission reduction targets involving a variety of fields, such as agricultural products, fossil energy, and industrial production [2,3]. Sugarcane is one of the critical strategic agricultural products, with global cane sugar production exceeding 75 million tons annually, of which China accounts for approximately 80 % of the total cane sugar production [4–6]. As one of the world's largest sugar-producing and consuming countries, accounting for the carbon emissions of cane sugar is an effective means to achieve the carbon emission reduction goal [7].

Life Cycle Assessment (LCA) is the most widely used method for calculating product carbon emissions, known as a systematic approach that covers the entire journey [8]. The boundaries for carbon emissions and types of greenhouse gases specified in the Intergovernmental Panel Climate Change (IPCC) guidelines are widely utilized internationally [9,10]. Meanwhile, LCA has been widely used to identify the production stages of agricultural products with high carbon emissions and to provide data support for carbon reduction techniques. The values of Greenhouse Gas (GHG) emissions from sugar [11,12] are mainly due to different boundaries and different types of products. There are problems of unclear accounting boundaries and inconsistent standards when accounting for carbon emissions over the whole life cycle of cane sugar. Determining the boundaries of carbon emission accounting for cane sugar is crucial. The LCA method can assess the carbon emission values of sugar produced from different raw materials and analyze the impacts of GHG emissions to find reduction pathways [13]. The cane sugar agro-industry can potentially reduce GHG emissions [14], especially in production. In particular, flue gas and wastewater discharged from the sugar production process have a great value in emission reduction. The carbon emissions from sugar, as a processed agricultural product with

* Corresponding author.
E-mail address: zhang.y@hit.edu.cn (Y. Zhang).
[1] Lixiao Luo and Wei Zhang are co-first authors of the article.

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high consumption, have been gradually emphasized by countries in existing studies. Internationally, LCA accounts for the majority of carbon emissions from the sugar industry, mainly because it is more accurate and can account for the whole process of the sucrose industry in different regions. However, China's research on carbon emission accounting for cane sugar is relatively limited and late in development, while a carbon accounting system for sugar production is still missing, and more specific measures are needed in this regard. Carbon emissions during sugar production are crucial to assessing GHG emissions from China's food system and are a fundamental means of achieving the goal of carbon neutrality. Establishing an accounting system for carbon emissions from China's sugar cane products is necessary.

Due to the biomass-oriented nature of sugarcane, the sucrose industry has enormous potential for carbon reduction [15,16]. Unlike other raw material industries, the cane sugar industry uses renewable plants to possess significant advantages in renewable resources and carbon sequestration [17]. As plants grow, carbon is fixed into sugarcane through photosynthesis. Sugarcane waste can be recycled, naturally degraded, or incinerated at the end of its lifecycle to recover electricity and heating energy. In sugar production, bagasse combustion generates electricity by releasing large amounts of highly concentrated carbon dioxide in the boiler exhaust gas, causing pollution [18]. As the most feasible post-combustion CO_2 capture technology, the chemical absorption method shows great promise for industrial applications. It mainly absorbs CO_2 through chemical reactions to generate unstable reaction products and utilizes reversal reactions to regain CO_2 and regenerate absorbent to achieve the purpose of capture [19,20]. Researchers [21] evaluated several typical decarbonization technologies based on four comprehensive evaluation indexes of technology, economy, environmental protection, and social benefits. The results show that the chemical absorption methods are ranked in the following order from the largest to the smallest: ammonia, MDEA, hot potassium alkali, and MEA. Compared with the MEA method, ammonia solution has many advantages, such as high absorption efficiency, low heat of absorption reaction, low corrosivity, and low raw material price. For most studies, the CO2 capture process and efficiency of ammonia-based capture technology are more of a concern. The utilization of its capture product, NH_4HCO_3 crystals, is also of particular importance [22]. Ammonium bicarbonate is widely used in agriculture, industry, food, pharmacy, and ecological management [23]. However, its utilization process is relatively cumbersome, and its economic value is low. Therefore, the high-value utilization of ammonium bicarbonate, a carbon capture product, is one of the most critical aspects of CO_2 capture and utilization technology. In the sugar industry, NH_4HCO_3 can be used as sugarcane fertilizer to replace nitrogen fertilizer in chemical fertilizer plants, a simple process with high benefits. It is of great significance to expand and study this issue accordingly.

However, the traditional ammonia CO_2 capture technology usually has the disadvantage of a low CO_2 absorption rate. To achieve efficient CO_2 capture, a new ammonia carbon capture technology using ammonia-ethanol chemical absorbent cross-linking is adopted, which improves a series of shortcomings of the traditional method [24]. The primary reaction is $NH_3 + H_2O + CO_2 = NH_4HCO_3$. The new ammonia-based carbon capture technology is based on the principle of dissolution crystallization. The solute in the form of crystals from the liquid phase of continuous precipitation separates the solvent and solute to get more ammonium bicarbonate to achieve sugar's carbon emission reduction goals. Applying new ammonia-based CO_2 capture can achieve the single-loop carbon emission reduction target for the flue gas-fertilizer cycle in sugar production.

The purpose is to construct a carbon accounting model for cane sugar through the LCA method while verifying that negative green carbon emissions have characterized sucrose products in China for the first time. A new ammonia carbon capture technology is proposed to achieve carbon emission reduction, recycling the carbon dioxide captured from the flue gas and fertilizers to improve the negative carbon emission potential of cane sugar products. Capturing carbon dioxide from flue gas and obtaining ammonium bicarbonate as nitrogen fertilizer reduces the cane sugar cycle's carbon emission intensity, increasing the sugarcane product's cumulative negative carbon emission throughout its life cycle. This will help build an accurate, scientific, and systematic greenhouse gas measurement system for key industries, which is significant in controlling CO_2 emissions in achieving China's national "Carbon peak and Carbon neutrality" goal.

Materials and methods

Full process of sugarcane product production

Take the sugar production in the Sugar Factory in Guangxi province as an example and conduct a carbon footprint assessment of the life cycle of cane sugar products. The total amount of sugarcane processed in 2022 is 800,000 tons, each consuming a certain amount of nitrogen fertilizer, compound fertilizer, and urea. The cultivation, harvesting, and transportation of each ton of sugarcane consumes 0.637 L of diesel fuel.

During the sugar production stage, the sugarcane undergoes various processes such as pretreatment, crushing, juice clarification, juice evaporation, sugar boiling, syrup separation, and drying, mainly consuming electricity [25]. The factory uses the residual bagasse to generate electricity through biomass boilers in sucrose production. The steam generated by the boilers drives backpressure steam turbines for production and daily use within the factory, and the surplus electricity is sold to the grid. The waste steam from the backpressure steam turbine is supplied to the evaporation, sugar boiling, drying, and other production equipment [26–28]. The secondary steam produced during evaporation is used to boil and heat sugar juice. In contrast, the condensate from the first and second-effect evaporation tanks can be returned to the boiler section for boiler feedwater. Finally, the sugar products produced are packaged in the packaging workshop to obtain sellable sugar products (white sugar). The process flow is shown in Fig. 1.

Application of new ammonia-based carbon capture technology

The carbon emissions in the sugarcane industry can be addressed using Carbon Capture, Utilization, and Storage (CCUS) technology [29,30]. The sugarcane bagasse boiler produces flue gas during combustion for power generation. Ammonia carbon capture technology can capture and utilize a portion of the CO_2 from the flue gas to produce agricultural fertilizers [31]. The new ammonia-based carbon capture technology enhances crystallization by dissolution precipitation and improves CO_2 uptake efficiency by cross-linking the ammonia-ethanol chemical absorbent. The flow of the new ammonia-based carbon capture technology is shown in Fig. 2. The principle is that CO_2 in the flue gas reacts with the ammonia absorbent in the absorption tower, forming a rich carbonic solution. When the loading capacity of the rich carbonic solution exceeds 0.48, the carbonation liquid is released and flows into the crystallizer, mixing with the precipitant ethanol [32,33]. Using precipitation, the solubility of the solute is significantly reduced, causing the carbonation product NH_4HCO_3 to separate in crystalline form, and after processing, it becomes the nitrogen fertilizer required for sugarcane growth [34]. Compared with the traditional process, the main feature of this technology is to mix the carbonation liquid with the solvent ethanol to produce solvent crystallization and to replace the carbonation liquid with the crystal product to produce thermal decomposition in the regeneration tower. The new ammonia carbon capture technology sometimes causes an inevitable loss of ammonia ethanol, so the carbon capture process needs to be supplemented with raw materials [35]. This method can save the energy required to heat the solvent water and significantly reduce the energy consumption of regeneration. Moreover, the crystal product can be decomposed at room temperature, so it can further reduce the regeneration energy consumption by utilizing the flue gas residual energy in the tail, thus realizing the cycle of

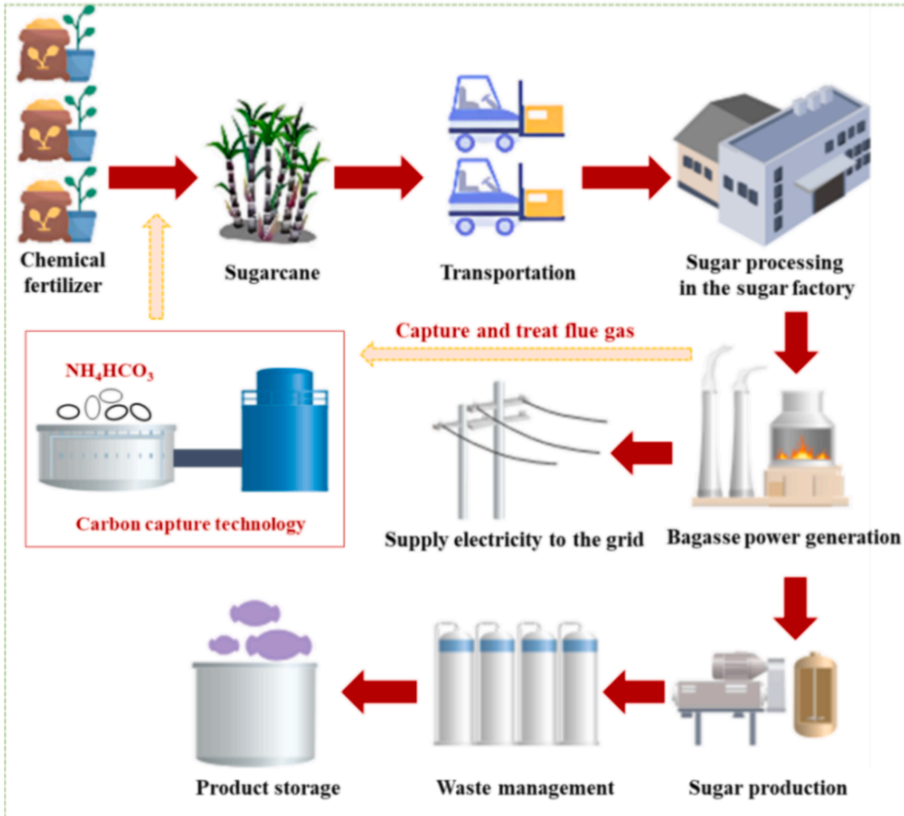


Fig. 1. Flowchart of sugarcane production and process.

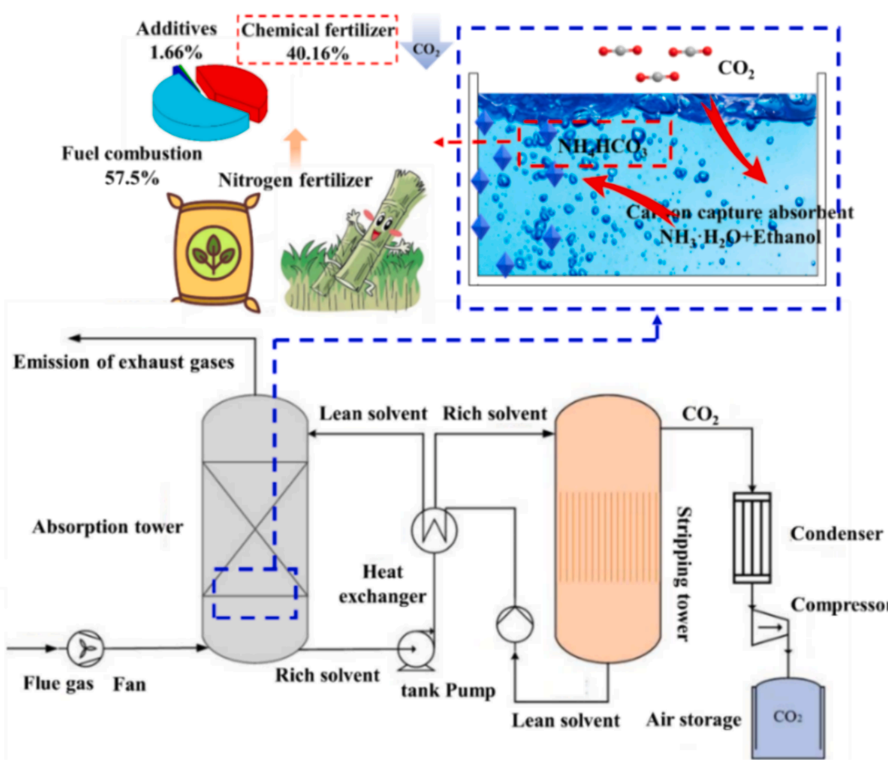


Fig. 2. Ammonia-based CO_2 capture used for the agricultural side of sugarcane production.

carbon capture [36]. The crystallization process of carbonized ammonia is enhanced by the antisolvent method, and the regeneration of the rich carbonized ammonia is replaced by crystal product regeneration. The problems of ammonia escape, low absorption efficiency, and high regeneration energy consumption in the decarburization process by ammonia are solved to some extent.

System boundary of sugarcane product production

Starting from the sugarcane product, the boundary for calculating the carbon emissions throughout its lifecycle includes the planting stage (sugarcane planting, growth, harvesting, and transportation), the production and processing stage (sugarcane processing, waste treatment, boiler combustion, steam power generation), and the product packaging stage (sugar packaging) [37]. The system boundary diagram is shown in Fig. 3. The new ammonia-based carbon capture technology for nitrogen fertilizer production adds ammonia water, ethanol, and electricity infrastructure, resulting in the byproduct NH_4HCO_3.

Depending on the source and destination of carbon, there are carbon emissions and carbon storage throughout the life cycle of sugar. At the sugarcane cultivation stage, carbon emissions result from consuming fertilizers and fuel. During sugar production, electricity consumption contributes to carbon emissions, and sugar production waste (*i.e.,* orange water filter sludge) contributes to carbon storage. Carbon storage is generated from power generation, residual bagasse, and waste baling at the bagasse burning stage. In the sugar packaging process, sugar is a product of carbon storage.

Life-cycle carbon emissions calculation model

For sugar production, the LCA method is applied to evaluate the GHG emissions from the whole value chain of sugar production, including the cultivation, processing, packaging, and storage stages. For the consumption stage, sugar is usually utilized to produce cakes, candy, and other products, which is not considered in this article. So, the carbon emissions calculation model for the LCA of sugarcane products constructed in this article is as follows:

$$C_{all} = C_1 + C_2 + C_3 - C_4 \tag{1}$$

Where:

C_{all} is the carbon emissions of sugarcane products over its lifecycle.

C_1 is the carbon emissions of sugarcane products during the cultivation stage.

C_2 is the carbon emissions of sugarcane products during the processing stage.

C_3 is the carbon emissions of sugarcane products during the packaging stage.

C_4 is the carbon storage of sugarcane products during the storage stage.

The specific carbon emissions calculation models for each stage of the lifecycle production process of sugarcane products are shown as follows:

(1) Sugarcane cultivation stage: As the third largest sugar producer in the world, China's main production areas include the provinces of Guangxi, Yunnan, and western Guangdong. The combined sugarcane cultivation of these provinces accounts for more than 90 % of China's total cultivation. Especially in the Guangxi Zhuang Autonomous Region, the sugarcane industry is the most influential and advantageous. This stage mainly includes carbon emissions from fertilizer application (nitrogen fertilizers, compound fertilizers, urea, etc.), fuel carbon emissions from mechanical sowing, harvesting, and vehicle transportation. The calculation formula is:

$$C_1 = \frac{\sum_{i=1}^{i} AR_i \times c_i \times 44}{A \times M_i \times 1000} + \frac{e_d \times W_m \times L_{am}}{A} \tag{2}$$

Where:

C_1 is the carbon emissions of sugarcane products during the cultivation stage.

AR_i is the amount of input of the fertilizer per ton of sugarcane.

c_i is the carbon content in the fertilizer.

M_i is the molar mass of the fertilizer.

A is the ratio of sugar produced by the company to the amount of sugarcane, %.

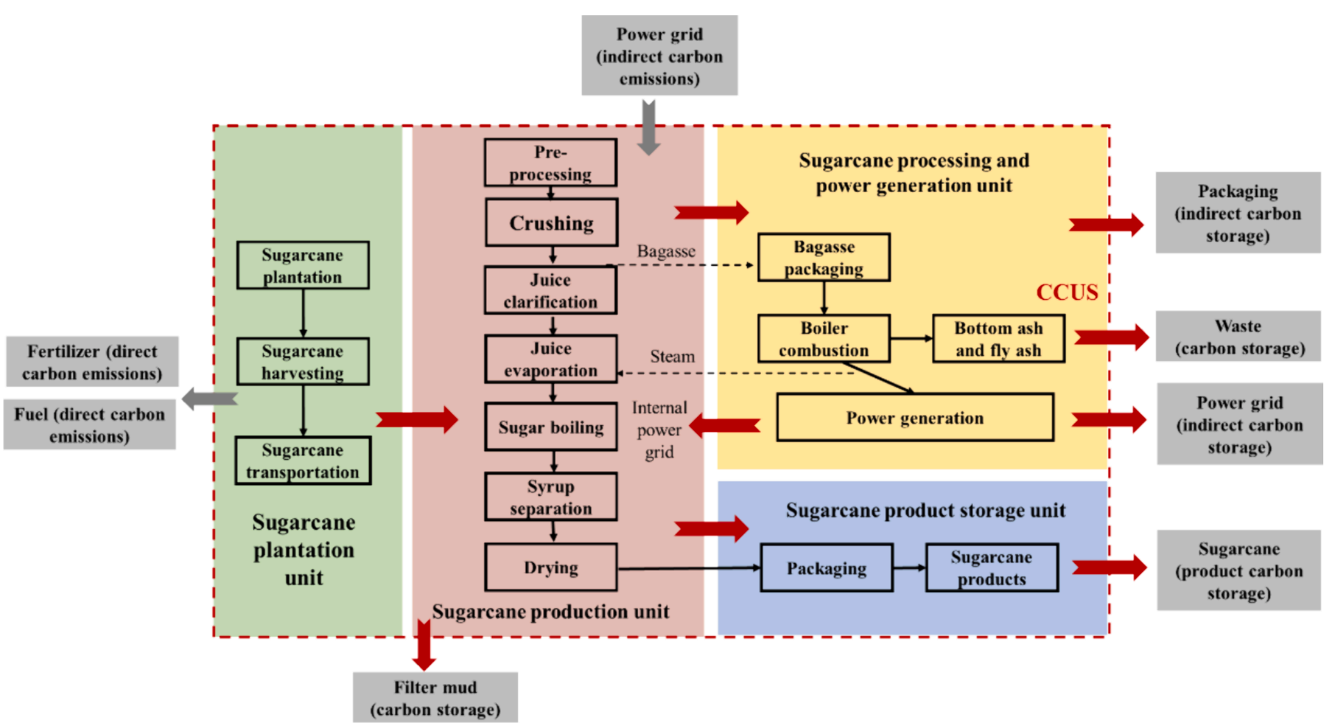


Fig. 3. System boundary diagram for carbon emissions of sugarcane products.

e_d is the carbon emission factor of the energy consumed during transportation (diesel, gasoline, etc.).

W_m is the fuel consumption on average during transportation.

L_m is the average transportation distance of sugarcane.

(2) Production and processing stage: Indirect carbon emissions caused by the net difference in electricity consumption from external and self-delivered electricity. CO_2 emissions from additives during the sugarcane juice clarification. Carbon storage from bagasse and filter mud. Meanwhile, water is recycled and used in small quantities, so the carbon emissions generated can be negligible. The calculation formula is as follows:

$$C_2 = \frac{(AD_{\text{grids}} - AD_{\text{sale}}) \times EF + \sum_{i=1}^{i} AO_i \times o_i - (AJ \times N_J + \text{AL} \times N_L)}{A} \tag{3}$$

Where:

C_2 is the carbon emissions of sugarcane products during the processing stage.

AD_{grids} is the self-consumption of electricity consumption per sugarcane.

AD_{sale} is the electricity delivered to the grid per ton of sugarcane positive for delivery and negative for purchase.

EF is the average annual emissions factor for electricity supply in the region.

o_i is the carbon emissions factor for the additive.

AO_i is the amount of input for sugarcane additives.

C_f calculation formula is as follows:

AJ is the carbon content received from juice produced by sugarcane.

N_J does sugarcane produce the amount of juice per extraction.

AL is the carbon content received from filter mud produced from sugarcane.

N_L is the amount of filter mud produced by sugarcane per extraction.

(3) Packaging stage: Packaging process for sugarcane products, calculation formula as follows:

$$C_3 = \frac{AP_{\text{wrap}} \times c_{\text{wrap}}}{A} \tag{4}$$

Where:

C_3 is the carbon emissions of sugarcane generated through packaging bags.

c_{wrap} is the carbon emissions factor for packaging bags of sugarcane.

AP_{wrap} is the amount of packaging bags used of sugarcane for sugar.

(4) Storage stage: Corresponding sugarcane products bring specific carbon storage, calculation formula as follows:

$$C_4 = \frac{\sum_{i=1}^{i} AT_i \times N_i}{A} \tag{5}$$

Where:

C_4 is the carbon storage generated by sugarcane.

AT_i is the carbon content received per unit of the sugar.

N_i is the production amount of the sugarcane product of sugarcane per extraction.

Carbon emission factors

Carbon emission factors are essential parameters in the carbon accounting process, and they can vary significantly between different countries and regions. The selection of carbon footprint factors for this article's lifecycle carbon emissions calculation model of sugar is based on references from the "PAS 2050 Specification" and the "IPCC 14067." For carbon emission factors that cannot be found in the corresponding guidelines, this study follows the following criteria for their selection [38,39]. ① Reference to relevant domestic databases; ② Reference to research articles in related fields. ③ Reference to foreign databases and research achievements [40,41]. The specific carbon footprint factors are shown in S-Table 1.

Results and discussion

Carbon emission results for sugar products' lifecycle

Based on the calculation method described earlier, activity data is collected, emission factors are determined, and relevant data is obtained. Applying the carbon emission calculation formulas (1) to (5) and using the carbon emission data from various processing units in a sugar mill can obtain the carbon emission calculation results for a sugar mill in Guangxi, as shown in Table 1. Since ammonia is purchased, its energy consumption is ignored in this calculation.

Table 2 shows the results of carbon emission accounting for cane sugar products using the new ammonia carbon capture technology.

From Table 1, it can be seen that the total carbon emissions throughout the lifecycle of sugar products are 1.0215 CO_2e/kg of sugar, the total carbon storage is 2.4473 CO_2e/kg of sugar, and the carbon footprint is −1.4259 CO_2e/kg of sugar. In the planting stage, fertilizer consumption contributes to a large amount of carbon emissions, especially compound fertilizer carbon emission value, which reaches 0.4813 CO_2e/kg of sugar. As seen from Table 2, the total carbon emission of the LCA method of the production of cane sugar products with the addition of the CCUS link is 1.2977 CO_2e/kg of sugar, the total carbon storage is 3.4471 CO_2e/kg of sugar, and the carbon footprint is −2.1494 CO_2e/kg of sugar. The CCUS technology is demonstrated to enhance the carbon-negative effect of the production process of cane sugar.

The carbon emissions and carbon storage at each stage of sugar production are shown in Fig. 4. By comparing Fig. 4(a) and Fig. 4(b), we can visualize the changes in carbon emissions at different stages of sugar production. The new ammonia carbon capture technology brings certain consumable losses in the processing stage, slightly reducing carbon storage. However, the ammonia carbon capture technology can bring

Table 1
Carbon emission results of sugar life cycle.

Stage	Item	Unit (sth/T)	Data	Carbon Data per Unit of Product
Planting	harvesting machine	L	0.0534	0.0011
	transport machine	L	0.0956	0.0019
	Nitrogen fertilizer	T	0.0093	0.1492
	Compound fertilizer	T	0.0257	0.4813
	Urea	T	0.0093	0.1439
	Transport fuel consumption	L	0.6378	0.0129
Processing	Calcium oxide	T	0.0036	0.0232
	Sulfur	T	0.0014	0.0044
	P_2O_5	T	0.0005	0.0027
	External electricity consumption	kWh	0.7952	0.0048
	External electricity delivery	kWh	0.1897	−0.0012
	Furnace slag	kg	0.0954	−0.0001
	Fly ash	kg	1.5953	−0.0029
	Orange water	kg	33.00	−0.0836
	Filter mud	kg	45.00	−0.2753
Packaging	Plastic bags	Pieces	2.468	0.2008
Product	White sugar	kg	131.88	−1.5437
	Bagasse	kg	73.21	−0.5407
Total carbon emissions		(CO_2e/kg of sugar)		1.0215
Total carbon storage				−2.4473
Carbon footprint				−1.4259

Table 2
Carbon emission results of sugar life cycle using CCUS technology.

Stage	Item	Unit (sth/T)	Data	Carbon Data per Unit of Product (CO_2e/kg of sugar)
Planting	Mechanical fuel consumption	L	0.0534	0.0011
	Mechanical fuel consumption	L	0.0956	0.0019
	Nitrogen fertilizer	T	0.0093	0.1492
	Compound fertilizer	T	0.0257	0.4813
	Urea	T	0.0093	0.1439
	Transport fuel consumption	L	0.6378	0.0129
Processing	Calcium oxide	T	0.0036	0.0232
	Sulfur	T	0.0014	0.0044
	P_2O_5	T	0.0005	0.0027
	External electricity consumption	kWh	0.9485	0.0057
	External electricity delivery	kWh	0.1897	−0.0012
	Furnace slag	kg	0.0954	−0.0001
	Fly ash	kg	1.5953	−0.0029
	Orange water	kg	33.00	−0.0836
	Filter mud	kg	45.00	−0.2753
CCUS	Ammonia solution	T	0.0016	/
	Ethanol	T	0.0194	0.2777
	NH_4HCO_3	T	0.1319	−0.9998
Packaging	Plastic bags	Pieces	2.468	0.2008
Product	White sugar	kg	131.88	−1.5437
	Bagasse	kg	73.21	−0.5407
Total carbon emissions		(CO_2e/kg of sugar)		1.2977
Total carbon storage				−3.4471
Carbon footprint				−2.1494

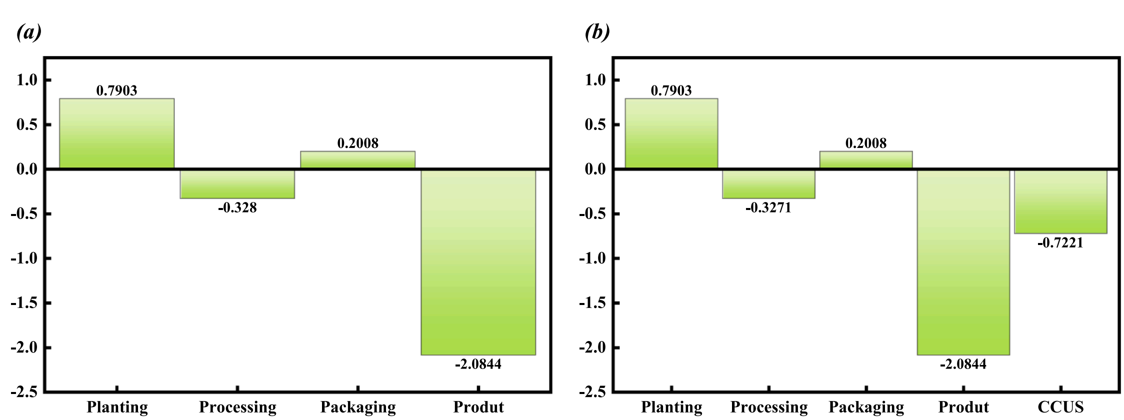
more carbon emission reduction, and its carbon storage can reach −0.7221 CO_2e/kg of sugar.

Results and analysis

The carbon emission data for each segment of the sucrose product is shown in Fig. 5(a). The total carbon emission of sugar product LCA is −1.0215 CO_2e/kg sugar. The contribution of carbon emissions varies among the different production stages of sugar products. Agricultural machinery has only a 0.1 % carbon impact. Agricultural fertilizers have the most significant effect at 46.9 %. Sugar cane cultivation in China has a high degree of mechanization in irrigation. Fertilizer application tends to rely more on manual labor [42]. The results illustrate that incompletely mechanized systems produce higher impacts than mechanized systems, possibly related to the lack of good water management and crop nutrition agronomic practices. Mechanized systems seem to consider using irrigation water and fertilizers more efficiently in fertilizer application and irrigation, resulting in small carbon emissions. The carbon emission from fuel consumption in the transportation stage is low at 0.0019, less than 0.1 % of the total carbon emission. Sugar production in China is characterized by clustering, and each link is closer to the other and consumes less fuel for transportation. From the data analysis, it can be concluded that reducing fertilizers and pesticides is an important measure to reduce emissions for the cultivation phase of sugar production. New biopesticides or recycled fertilizers can replace chemical fertilizers and pesticides. Meanwhile, through the Internet of Things (IoT) technology, we can further realize the precise application of fertilizers, irrigation, and pesticides, and effectively improve the efficiency of cultivation. Healthy lifestyles of the public should be disseminated, which will limit or even reduce the demand for sugar products. This is also an important way to reduce greenhouse gas emissions from sugar production.

On the other hand, sugar mills use bagasse boilers for biomass combustion and power generation, and external electricity consumption generates only 0.1 % of carbon emissions. The main reason for this is that the steam generated by the boiler drives a back-pressure turbine for internal production and domestic use, while the remaining electricity is sold to the grid. In this way, waste is utilized, and the electricity generated can be consumed internally, reducing external electricity consumption. In the packaging stage, due to the use of plastic products for product packaging, the carbon emissions value is 0.2008, and the average consumption of plastic bags per kg of sugar is 2.468 pieces. Since implementing the Renewable Energy Law, biomass utilization in China has mainly focused on power production applications [43]. This includes agricultural and forestry biomass power generation, waste incineration power generation, pyrolysis/gasification power generation, and biogas power generation. The carbon emission intensity of power generation using bagasse in sugar production is less than 1.8 %, 2.1 %, and 3.8 % of that of coal, fuel oil, and gas. The rational and full utilization of bagasse power generation is a critical way to reduce regional fossil energy consumption, improve energy structure, and reduce greenhouse gas emissions.

Sugar carbon emission data using the new ammonia carbon capture technology is shown in Fig. 5(b). The total carbon emission is 1.2977 CO_2e/kg of sugar. The carbon footprint is 18.7 % higher than sugar



(a) Carbon emissions and storage of sucrose without ccus technology   ***(b) Carbon emissions and storage of sucrose with ccus technology***

Fig. 4. The carbon emissions and carbon storage at each stage of sugar production.

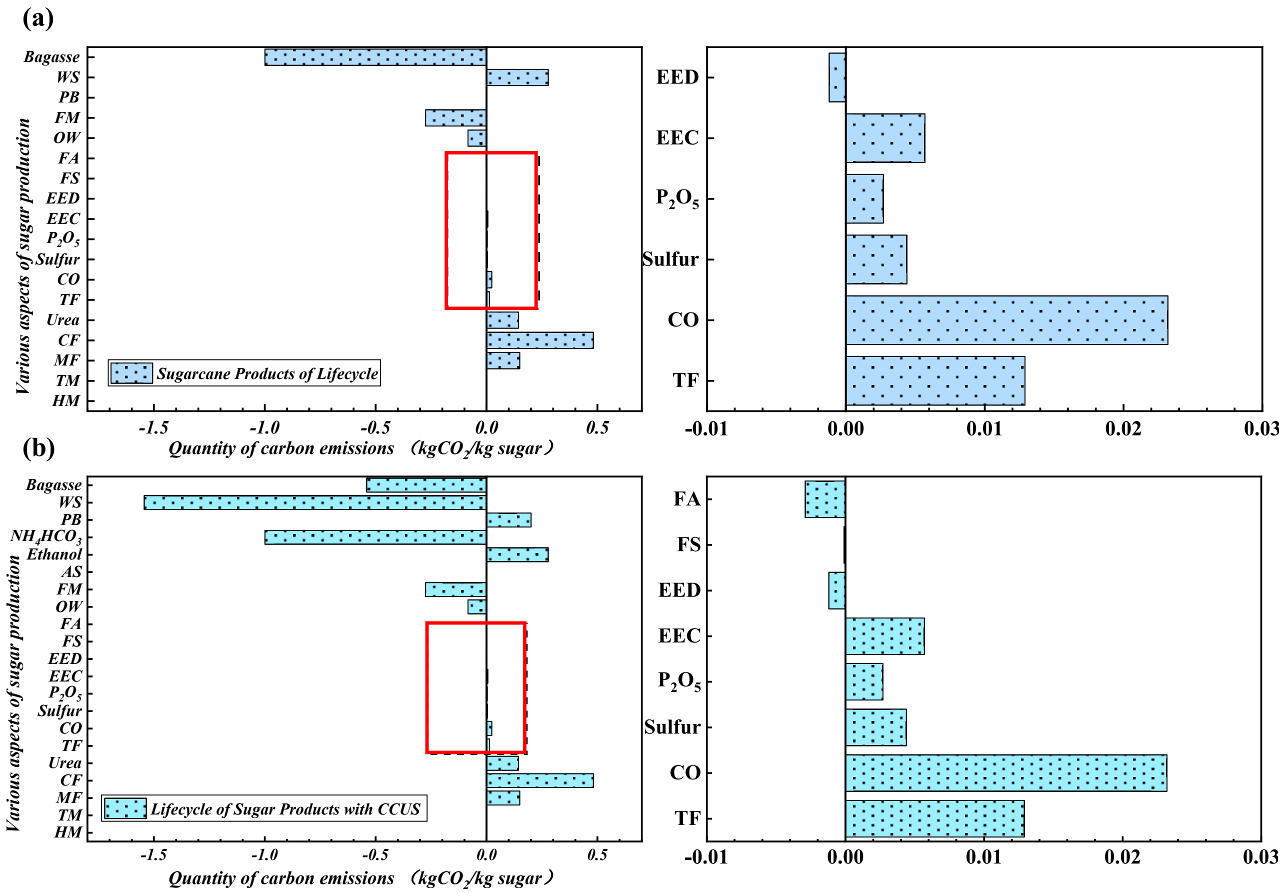


Fig. 5. Carbon emission results of sugar life cycle.

production without ammonia carbon capture technology. The main influencing factors are the increased consumption of ammonia and ethanol due to the application of the new ammonia carbon capture technology and the associated transportation and storage costs that need further improvement. However, the increase in carbon emissions is slight because ammonia can be recycled and lost in the carbon capture process. According to the Peak Carbon Action Plan for 2030, GHG emissions from the sugar processing stage must be reduced by 47.3 % [44]. Due to the pressure to reach Peak Carbon by 2030, it is crucial that energy consumption at the sugar processing stage is reduced, and the new ammonia carbon capture technology can bring about carbon reduction to a certain extent.

As shown in Fig. 6(a), the total carbon storage of the whole life cycle of sucrose products is −2.4473 CO_2e/kg sugar, of which the storage of sucrose accounts for 63.1 %. The main influencing factor is sugarcane, a green photosynthetic plant that absorbs carbon dioxide and releases oxygen during its growth process. Therefore, sugarcane is a typical carbon-negative material. The entire life cycle carbon footprint of sugar products is −1.4259 CO_2e/kg sugar, proving that the production process of sugar products in China is carbon-negative. It can be seen that the carbon storage of furnace slag, fly ash, orange water, filter mud, white sugar, and remaining bagasse are −0.0001 CO_2e/kg of sugar, −0.0029

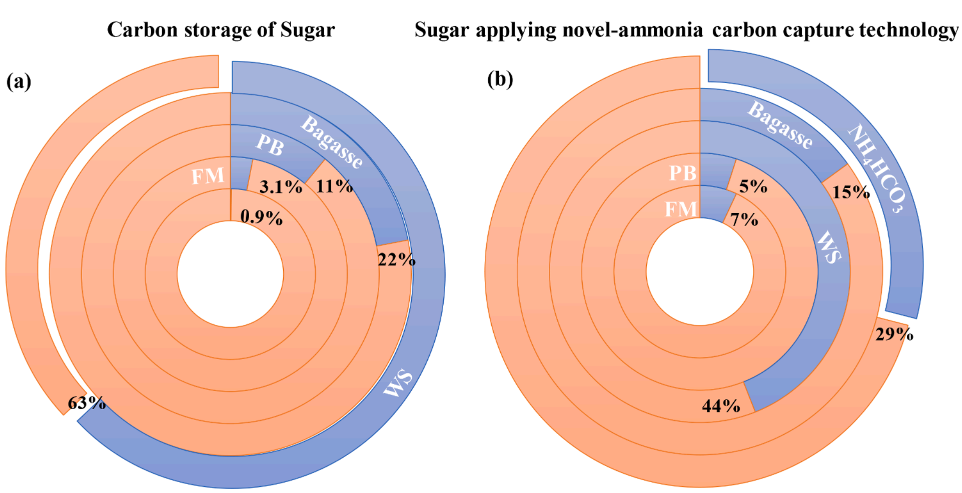


Fig. 6. Carbon emission results of the sugar life cycle.

CO_2e/kg of sugar, −0.0836 CO_2e/kg of sugar, −0.2753 CO_2e/kg of sugar, −1.5437 CO_2e/kg of sugar, and −0.5407 CO_2e/kg of sugar, respectively. Their proportions are 0.3 %, 0.3 %, 0.3 %, 3 %, 11 %, 22 %, and 63 % respectively. Carlos et al. [44] studied the sugar industry in Mexico, which has a carbon footprint value ranging between −0.45 and −0.63 CO_2e/kg of sugar. Yu et al. [45] estimated the GHG emissions of sugarcane cultivation and milling process based on the carbon footprint of sugar produced from sugarcane in Thailand −0.55CO_2e/kg of sugar. Compared with studies in other countries, the GHG emission intensity of sugar production in China is lower and more carbon-negative. With the development of the economy and the improvement of people's living standards, the demand for sugar in China will continue to increase. As a green carbon-negative product, sugar cane is expected to gain long-lasting benefits by implementing carbon trading policies.

As shown in Fig. 6(b), the total carbon stock is −3.4471 CO_2e/kg sugar, and the carbon footprint is −2.1494 CO_2e/kg sugar. The carbon footprint is 41.4 % higher than the negative carbon of sugar production without using ammonia carbon capture technology. During sugarcane cultivation, carbon dioxide is recovered and made into nitrogen fertilizer by ammonia carbon capture technology, which achieves the goal of reducing carbon emissions from fertilization. There is a significant variation in the proportion of carbon stored in the production of cane sugar products. The proportion of carbon stored in the nitrogen fertilizer produced is 29 %. Carbon capture from ammonia can be recycled, and the production of excess nitrogen fertilizers also produces large carbon stocks, thus increasing the degree of carbon negativity. The new ammonia carbon capture technology captures the CO_2 in the waste flue gas of the sugar mill, and the new ammonia carbon capture process product, ammonium bicarbonate, is obtained, which has significant advantages in crop fertilization. This proves the new ammonia carbon capture technology can capture some CO_2 from the flu and make agricultural fertilizers. It is unique in realizing the utilization of by-product resources and improving environmentally soundness.

Sugar is a fundamental human demand. The research adopts the LCA method to calculate the carbon emissions of cane sugar production. Compared with existing studies, the entire life cycle of the cane sugar industry can better depict the whole carbon footprint of the cane sugar industry. Overall, the sugar industry is green and carbon-negative, a green product that realizes the carbon reduction target. As living standards improve, China's demand for sucrose will increase, but GHG emissions from cane sugar production will decline significantly as new technologies are utilized. Production efficiencies are enhanced while the energy mix is transformed. Food and other sugar-related industries will benefit.

Conclusion

(1) A complete life-cycle carbon emission calculation model for cane sugar products in China has been established based on the LCA methodology. Carbon emission accounting has been conducted for the planting, harvesting, transportation, processing, waste treatment, packaging, and other aspects of the multi-temporal and multi-scale sugar industry. The negative carbon footprint of the whole life cycle of sugarcane sugar products is −1.4259 CO_2e/kg sugar.

(2) A novel ammonia-based CO_2 capture technology based on dissolution crystallization is proposed. It shows a carbon footprint of −2.1494 CO_2e/kg sugar with an elevated negative carbon amount. Nitrogen fertilizers are prepared by recovering carbon dioxide from the flue gases of sugar mills, achieving a single cycle of negative carbon emissions from cane sugar preparation.

(3) China's green and efficient sugar industry needs to be emphasized as a big sugar country. In the future, the preparation of cane sugar must be developed to reduce energy consumption and harmful carbon emissions. The accurate carbon monitoring platform can be established based on the carbon accounting model of the LCA method. At the stage of sugarcane cultivation, carbon emissions can be reduced by replacing standard agricultural supplies with new bio-pesticides or recycled fertilizers. In the processing stage, the pollution of tail flue gas is reduced through emission reduction technology to accelerate the process of green transformation of China's sugarcane industry.

CRediT authorship contribution statement

Lixiao Luo: Writing – review & editing, Writing – original draft, Visualization. **Wei Zhang:** Resources, Investigation. **Yu Zhang:** Resources, Investigation. **Dongdong Feng:** Investigation, Formal analysis. **Yuzhi Li:** Resources, Investigation. **Xishan Zhu:** Supervision, Project administration. **Haibo Ye:** Project administration, Investigation. **Weichong Chen:** Supervision, Project administration. **Yingsen Qin:** Supervision, Project administration.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2024.103858.

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