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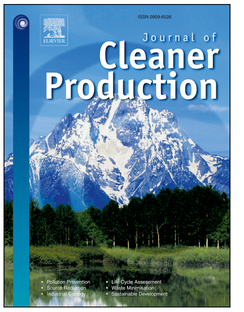

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Integration of spent coffee grounds valorization for co-production of biodiesel and activated carbon: an energy and techno-economic case assessment in China

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ABSTRACT

Over 10 million tons of coffee were consumed globally every year, resulting in an enormous amount of spent coffee grounds (SCG) waste to be processed. However, in many parts of the world, the SCG is treated as general waste and usually ends up in landfill or incineration. This practice is a waste of resource and also can cause environmental pollution. SCG has a fine cellulosic fiber structure and contains a considerable amount of lipid. It can be considered as a promising feedstock for bioenergy and biomaterials production. Before building a processing plant, it is essential to evaluate the feedstock characteristics and thermal conversion routes to fully understand the process's technical feasibility and economic viability. This work developed a comprehensive process model for the integrated SCG valorization process to evaluate the energy flow, process efficiencies, and costs for co-production of biodiesel (BD) and activated carbon (AC) in Changsha, China. The results showed that the SCG valorization system can co-produce BD, AC and glycerol with product yields of 13.41%, 14.06% and 2.24% (wet feed basis), respectively. The overall process efficiency was calculated to be 30.5%. The fuel gas produced from the pyrolysis process can meet part of the process heat demand, but additional natural gas is required to provide sufficient heat for the conversion process. Significant energy consumption occurs in hexane recovery, char activation, and SCG carbonization subsystems, accounting for 39.4%, 21.0%, and 18.4% of the total energy consumption, respectively. The minimum selling prices of the BD and AC are calculated to be CNY 1.83/kg and CNY 4.42/kg, respectively, which are well below their current market prices. The base case scenario can make the plant profitable, but the investment return and payback time may not be attractive enough to the investors. Process developers should identify optimum plant locations and endeavor to improve the market values of the products in order to enhance the economic viability.

Keywords: Spent Coffee Grounds; Biodiesel; Activated Carbon; Pyrolysis; Techno-economic Assessment

1. Introduction

Coffee is one of the most popular beverages worldwide. According to the International Coffee Organization, the annual production of coffee in the world increased by 59.3% in the recent twenty years, from 6.36 million tons in 2000 to 10.13 million tons in 2020. Forecast analysis of past data indicated that the world annual output of coffee would reach 11.67 million tons in 2025 [1]. In recent decades, China has become an emerging and highly dynamic coffee market with an annual growth of coffee consumption being up to 15%. This is far higher than the average global growth rate of 2%. It is estimated that China's coffee market could reach CNY 217.1 billion (equivalent to USD 33.6 billion) in 2025 [2].

Coffee spent grounds (SCG) is the solid residue from coffee beans after the coffee brewing or extraction process. When processing raw coffee beans, 65% of the dry mass remains as the SCG [3]. The SCG contains considerable amounts of lipid and valuable chemicals, such as caffeine, tannic acid and polyphenols. However, in many parts of the world, the SCG is treated as general waste for landfill or incineration. This practice is a waste of resources and also pollutes the environment. As it is derived from the coffee brewing stage, SCG usually presents a very high moisture content (over 60%). The wet SCG waste is a particular challenge to the environment, as its natural degradation produces greenhouse gases and promotes the growth of toxic microorganisms contaminating solid and waste sources.

Since it has been finely ground, SCG is in fact an excellent source for the extraction of cellulose and hemicellulose, which makes up to 50% of its dry mass. They can also be processed for bioethanol production by fermentation and bio-composites by using polypropylene matrix [4]. There are examples of converting the lipid in the SCG to biodiesel (BD) through transesterification [5, 6], as well as deriving activated carbon (AC) by physical or chemical activation methods [7, 8]. The co-production of BD and AC from the SCG is considered a highly efficient valorization of coffee waste. For understanding the process technical feasibility, it is necessary to analyze the mass balance and the energy flow of each step in the overall production process.

Previous research has addressed the techno-economic evaluation of BD production based on different scenarios. Kookos et al. [3] performed a techno-economic assessment on a 1,000 t/a BD production process from SCG by lipid transesterification. It was found that the cost of production for BD was USD 2.9/kg and the total cost of plant investment was USD 9.976 million. The authors claimed that the SCG valorization process could be economically attractive when a centralized production system was established. Kamil et al. [9] performed the economic assessment on BD production from SCG in an 8,000 t/a plant. The results showed that the annual capital cost and annual operating cost (OC) were USD 15.12 million and 1.91 million, respectively. The BD production cost was found to be USD 0.24/kg, which was considered the lowest price compared to other common oil feedstocks for BD production. This was due to the cost of the SCG feedstock was free of charge. They concluded that the process could generate a positive internal rate of return (IRR) of 45%, and this indicated that the process of SCG to BD production project could be worth investing in. Kamil et al. [10] explored the economic and technical feasibility of using SCG as a feedstock for BD production. It was found that the minimum selling price (MSP) of BD in the 1,025 t/a BD plant was USD 1.13/kg (3.54/gal). The authors concluded that the SCG BD production plant could be economically viable when the production capacity is over 10,000 t/a. Researchers also performed comprehensive assessments on the direct conversion of wet feedstock into chemical intermediates (i.e. carboxylic acids) that could form building blocks for biodiesel, and they concluded that the thermal and biological conversions could give products with a cost lower than their market values [11, 12].

Techno-economic evaluation on BD production has also been evaluated for using other feedstocks. Table 1 summarized the recent publications and their key data on producing either BD or AC from various feedstocks, including AC produced from unusual wastes, such as particleboard and spent mushroom substrate through carbonization and physical activation process. Naveenkumar et al. [13] studied using zinc doped calcium oxide as a nanocatalyst for BD production from castor oil. A process simulation on a 20,300 t/a plant was carried out. The economic analysis on the plant presented a production cost of USD 0.77/kg, a payback time (PBT) of 2.88 years and an IRR of 30.46%. The author claimed that feedstock cost and BD price were the major factors affecting the viability of the process. Naveenkumar et al. [14] evaluated the techno-economic performance of the statistical optimization of BD production from Calophyllum inophyllum oil using Zn doped CaO nanocatalyst. With a total plant capital investment of USD 2,753,000, the plant would generate a PBT of 1.15 years and an IRR of 66.9%. The authors recommended that catalyst and MeOH should be recovered to reduce the OC and improve the quality of BD. Arora et al. [15] evaluated a BD production plant using cane oil. It was found that a 1,600,000 t/a cane oil plant would generated an IRR of 51.9% and the MSP of BD was USD 1.15/kg. Sensitivity analysis on the process showed that the change in cane oil percentage and cane oil procurement price were important for the process economics. Lee et al. [16] evaluated the production of BD from waste cooking oil using solid-biochar as the catalyst for transesterification. The analysis results showed that the total plant investment was USD 54.4 million and the BD production cost was USD 1.8/kg. The methanol price was the most sensitive factor of BD production cost. The authors claimed that subsidy for BD and tax exemption for energy production could be a promising prospect. Faird et al. [17] conducted a techno-economic evaluation on a 3.68 million tons per year plant, which produced BD from locally collected waste cooking oil. The results shown the BD production cost, PBT and IRR were USD 0.54/kg, 1.05 years and 60%, respectively. The authors claimed that the project was suggestively lucrative by evaluating these economic indicators and was able to endure the change of plant capacity and raw material price. However, it is also worth noting that this was concluded from calculating the cost of biodiesel conversion process, without fully considering the cost of collecting, storing and transporting the highly dispersed waste cooking oil for feedstock. Vanreppelen et al [18] evaluated the techno-economic performance of a process design for the production of high value nitrogenized AC using co-pyrolysis a mixture of particle board and melamine formaldehyde. It was found that the AC production cost and IRR of the project were USD 2.07/kg and 38% respectively. The sensitivity analysis on the project indicated that the economics was sensitive to the investment cost, the product yield and the AC selling price. Liu et al [19] conducted a techno-economic assessment on the AC production process. The capital cost of the process was USD 9.64 million and the IRR and PBT were 35% and 3.04 years respectively.

Table 1 The techno-economic analysis of BD and AC production process

Feedstock	Product	Plant scale (t/a)	Prod. cost (USD/kg)	Prod. cost (CNY/kg)	PBT (year)	IRR (%)	Ref.
Castor oil	BD	20,300	0.77	5.03	2.88	30.46	[13]
Calophyllum inophyllum oil	BD	21,000	0.68	4.45	1.15	66.90	[14]
Cane oil	BD	1,600,000	1.11	7.52	1.55	51.90	[15]
Waste cooking oil	BD	37,879	1.8	11.77	1.91	44.50	[16]
Waste cooking oil	BD	3,680,000	0.54	3.53	1.05	60.00	[17]
Particle board	AC	20,000	2.07	13.53	2.10	38.00	[18]
Spent mushroom substrate	AC	62,000	2.56	16.74	3.04	35.00	[19]

Although the previous research addressed the experimental or techno-economic analysis of producing BD and AC from the SCG, there is still a significant knowledge gap in the co-production of these valuable products with particular considerations on the practical process and energy integration with a comprehensive economic assessment. This work presents a comprehensive techno-economic evaluation of SCG valorization for co-production of BD and AC based in China. The modelled process describes the detailed integration of the SCG processing including the feedstock handling and drying, oil extraction and conversion to BD from SCG, and defatted SCG (DFSCG) carbonization, activation and conversion to AC. Substantial contributions have been made in the in-depth study on the economic performance and the parameters with significant impacts on the process feasibility and the plant's viability. The overall process mass balance and energy flow were developed based on data carefully selected from the high-quality literature. The results of system performance and process efficiency were employed in the economic performance evaluation model to calculate the MSPs of the products and their sensitivity to the variation of a series of factors. Finally, the internal rate of return and expected investment payback were analyzed in order to provide constructive recommendations for the practical development of the process.

2. Material and methods

2.1 Material definition and characteristics

Table 2 presents the results of proximate and ultimate analyses of the typical SCG and defatted SCG (DFSCG) taken from experimental tests. SCG usually contains 10-15 wt% oil [3]. In this work, the oil content is taken as 14.1%, in line with the literature [10, 20].

Table 2 Proximate and ultimate analyses of the SCG and DFSCG feedstock

Samples	Proximate analysis [a] (wt%)				Ultimate analysis [b] (wt%)					Lower calorific value [b] (MJ/kg)
	Moisture	Volatile	Ash	Fixed carbon	C	H	O*	N	S	
SCG	6.98	64.94	7.05	21.30	56.10	7.20	34.00	2.40	0.14	21.30
DFSCG	6.04	65.88	9.20	18.88	51.80	6.30	38.80	2.80	0.17	20.80

a Dry-ash free basis; b Air dried basis; * By difference.

SCG is the solid residue obtained after the brewing process of roasted coffee, which results in significant moisture content in the SCG. DFSCG is gained after the extraction of oil from SCG. The carbon contents in SCG and DFSCG are 56.1% and 51.8%, respectively [21], indicating high carbon content and suitability for producing carbon-based materials [22]. The coffee oil extracted from SCG is used to produce BD, while the remainder DFSCG is used to produce AC. The coffee oil is suitable for BD production, and it is very stable as it has a high content of antioxidants. DFSCG has a good level of heating value (20 MJ/kg), and it can be usually combusted as a solid fuel to provide process heat instead of conventional fuels [23]. In the present work, the DFSCG is processed to produce AC for high-value product recovery.

2.2 Integrated SCG valorization system

The proposed SCG valorization system consists of five major subsystems: feedstock pre-treatment, oil extraction, waste treatment and disposal, BD production, and AC production. The system boundary of the process model involves all the processing steps from SCG reception through co-production of BD and AC to waste disposal. Feeding the received SCG into the process inlet is the start point of the model. There are three endpoints of the model: *i.* the output of the BD, *ii.* the output of the AC and *iii.* the outlet of ash and wastewater for disposal.

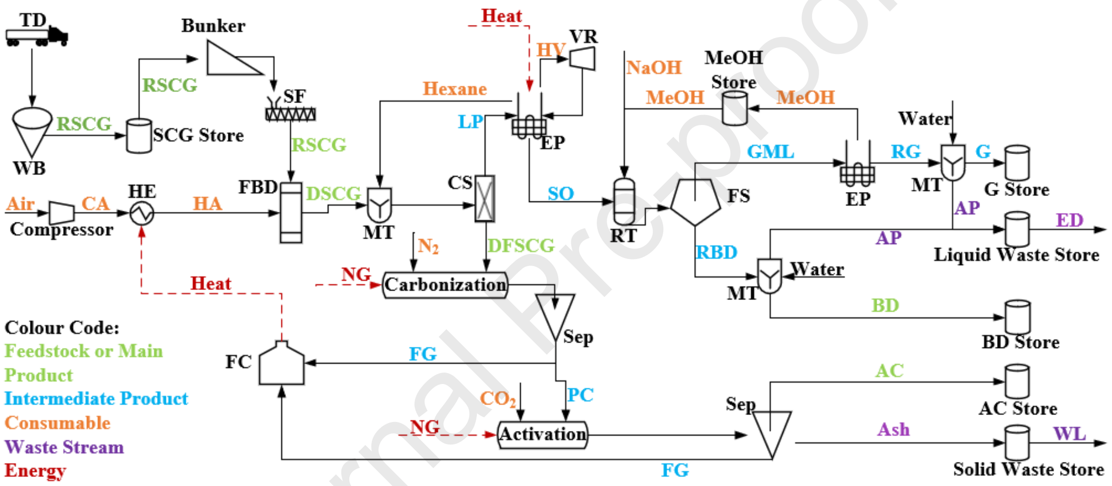

Fig. 1 Schematic diagram of the integrated SCG utilization system.

(AC: Activated carbon, AP: Aqueous phase, BD: Biodiesel, CA: Compressed air, CS: Centrifugal separator, DSCG: Dried SCG, DFSCG: Defatted SCG, ED: Effluent discharge, EP: Evaporator, FBD: Fluidized bed dryer, FC: Fuel combustor, FG: Fuel gas, FS: Fluid separator, G: Glycerol, GML: Glycerol and MeOH liquid, HA: Heat air, HE: Heat exchanger, HV: Hexane vapor, LP: Liquid product, MT: Mixing tank, NG: Natural gas, PC: Pyrolysis char, RBD: Raw biodiesel, RG: Raw glycerol, RSCG: Raw SCG, RT: Reaction tank, SF: Screw feeder, SO: SCG oil, TD: Truck delivery, VR: Vapor recompression, WB: Weigh bridge, WL: Waste landfill)

As shown in Fig. 1, the SCG feedstock is first received, weighed, and sent for drying. Upon drying, the processed feed is sent to the mixing tank with hexane in order to extract coffee oil from SCG. The DFSCG is separated from the solvent in a nozzle centrifugal separator. The hexane recovery is carried out in an evaporator for recycling. The DFSCG is carbonized and activated to produce AC, and the fuel gas produced in the carbonization and activation processes is combusted to provide heat for the system.

The coffee oil is transesterified with MeOH to produce BD and glycerol under suitable conditions. The wastewater produced in the BD and glycerol purification process is treated as a waste effluent. The following sections present the detailed processing stages and conditions for the integrated process.

2.2.1 Feedstock handling and drying

It is necessary to pre-treat the received SCG to ensure the characteristics of the SCG meet the requirement of the process. On feedstock delivery, the received SCG is weighed on a weighbridge at the site and thereafter stored in a concrete storage building. The wet SCG (containing 65 wt% moisture) is then sent to the fluidized bed dryer by a screw feeder with a feed rate of 5 tons per hour (base case). The fuel gas produced from the pyrolysis of DFSCG is used to provide heat for drying. The drying stage produces 1,750 kg/h of DSCG.

2.2.2 Oil extraction and DFSCG production process

Hexane is selected as the extractant for coffee oil with a ratio of 14.1% to the DSCG [24]. Hexane is sent to the mixing tank along with the DSCG for 45 min for oil extraction to obtain oil-rich hexane and the DFSCG [9]. The DFSCG produced is separated in a nozzle centrifugal separator, where the DFSCG is continuously discharged through nozzles. The clarified liquid is discharged and sent to an evaporator for oil and hexane separation. The recovered hexane is recycled to the mixing tank for the next round of the extraction process. The loss of hexane is taken as 10 kg per ton of oil extracted [25].

2.2.3 Production of BD

The BD is produced in three steps, namely transesterification, BD purification and MeOH recovery. The coffee oil reacts with MeOH under the promotion of NaOH catalyst to produce methyl oleate ($C_{19}H_{36}O_2$) and glycerol ($C_3H_8O_3$) through transesterification Eq. (1):

$$C_{57}H_{104}O_6 + 3CH_3OH \rightarrow C_3H_8O_3 + 3C_{19}H_{36}O_2 \qquad (1.)$$

The reactants were agitated at 450 rpm in the reaction tank with an oil: MeOH molar ratio of 6:1 at a constant temperature of 60 °C for 90 min [20]. The mass of NaOH catalyst is selected as 1.5% of the coffee oil. The mass proportions of BD and glycerol in DSCG are 13.41% and 2.24%, respectively.

The glycerol produced settles at the bottom of the reactor, while the BD layer (methyl oleate) remains at the top phase. The two layers are separated using a decanter after the glycerol is fully settled under gravity. The raw BD obtained after separation contains impurities including NaOH, MeOH, soap and glycerides. A multi-stage washing process with static washing and two rounds of foam washing was performed. Water washing is used for the BD purification process, with water consumption of 5% to the raw BD.

The mixture of glycerol and MeOH is sent to a nozzle centrifugal separator for soap removal. After that, the mixture is sent to a distillation column for MeOH and glycerol separation. The MeOH recovery was performed at 60 °C and 0.4 MPa with a recovery rate of 90.1% [26].

2.2.4 Production of AC

The AC production process mainly involves carbonization and activation. The carbonization kiln is heated to 500 °C, which gives the maximum char yield [27]. The fuel gas (vapor and gaseous product from pyrolysis) is recycled to the combustor to provide heat for the whole process.

The activation step occurs in the CO_2 environment at 800 °C [28], eliminating the impurities adsorbed on the char, increasing pore size and volume, and forming the active sites on the outer surface.

2.2.5 Waste disposal

Most process waste from the plant is wastewater, mainly produced from raw SCG drying and purification of BD and glycerol. The wastewater from the transesterification process generally contains BD, glycerol, NaOH, MeOH and soap. The aqueous liquid is disposed of through industrial sewage works at a high cost because the wastewater normally has a high chemical oxygen demand value. It is assumed that the exhaust emission from the combustor fully meets the local emission regulation. For the base case analysis, the ash from the combustor is sent offsite for disposal by means of the landfill at a cost. It is worth mentioning that the ash may be accepted and taken away by a local fertilizer or cement production plant without incurring any cost. However, due to the lack of established market mechanism and logistic arrangement for ash recycling in China, it was decided the ash to be treated as plant waste.

2.3 Process mass and energy balances

A spreadsheet model was developed to evaluate the process mass balance and energy flow of the conversion process (Fig. 1). The process model employs single linked worksheets containing all the subsystem components presented in Section 2.2.

Table 3 Key process parameters used in the spreadsheet model

Product yields (dry feed basis)	**Unit**	**Value**	**Reference**
SCG oil	wt.%	14.1	[10]
BD	wt.%	13.4	[29]
AC	wt.%	14.1	[30]
Glycerol	wt.%	2.28	[3]
Fuel gas	wt.%	18.0	[30]

Fuel gas composition	**Unit**	**Value**	**Reference**
N_2	vol.%	3.5	[19]
H_2	vol.%	1.0	[19]
O_2	vol.%	0.5	[19]
CO	vol.%	55.5	[19]
CO_2	vol.%	29.0	[19]
CH_4	vol.%	1.5	[19]
H_2O	vol.%	9.0	[19]

Energy content	**Unit**	**Heating value**	**Reference**
SCG (dry)	MJ/kg	23.4	[21]
SCG oil	MJ/kg	38.0	[9]

BD	MJ/kg	39.6	[21]
AC	MJ/kg	33.5	[31]
Glycerol	MJ/kg	18.1	[32]
Fuel gas	MJ/kg	14.8	[31]
Natural gas (NG)	MJ/Nm^3	43.5	[33]

Table 3 presents all the key process parameters used in the spreadsheet model. The carbonization, activation and hexane recovery processes are the primary energy-consuming processes within the plant. Therefore, the process efficiency and economic viability of the whole process largely depend on the energy consumption of these three processes. The heat requirement of the carbonization, activation and hexane recovery was estimated to be 1539.7, 1760.8 and 3298.7 kJ/(kg•h), respectively, of the as received SCG feedstock. These results are calculated based on the energy requirement for pyrolysing the DFSCG, activating char and heating up the solvent. The energy efficiencies of the heat exchanger and the fluidized bed dryer used in this work are 85 % and 64 %, respectively [34, 35]. The process efficiencies were calculated as the proportion of products energy content out of the total energy input from the SCG and additional fuel (natural gas). The process efficiencies are calculated as:

$$\eta_{\mathrm{BD}} = \frac{E_{\mathrm{BD}}}{E_{\mathrm{SCG}} + E_{\mathrm{NG}}} \times 100\% \qquad (2.)$$

$$\eta_{\mathrm{AC}} = \frac{E_{\mathrm{AC}}}{E_{\mathrm{SCG}} + E_{\mathrm{NG}}} \times 100\% \qquad (3.)$$

where E_{SCG} and E_{NG} are the energy contents of SCG and NG, kW/a (shown in Table 3); E_{BD} and E_{AC} are the power outputs of BD and AC, respectively, kW/a. The SCG valorization process efficiency is the product energy output out of the total energy in SCG and NG. The overall efficiency is the sum of η_{AC} and η_{BD}.

3 Economic evaluation

3.1 General assumptions

This study was conducted in the year 2020. In order to the present all the cost up to date, other non-2020 cost used was updated with an assumed inflation rate of 3%. The equipment cost values collected before 2020 have been adjusted to the latest values by using the Chemical Engineering Economic Indicators (EI): EI_{2014} = 586.8, EI_{2015} = 592.0, EI_{2016} = 606.0, EI_{2017} = 623.5, EI_{2018} = 638.1, EI_{2019} = 652.9 and EI_{2020} = 668.0 [36]. Some cost data was collected in the currency of USD and GBP. They were converted at the rates of USD : CNY = 1 : 6.4944, EUR : CNY = 1 : 7.8567 and GBP : CNY = 1 : 9.0545. It is assumed that the plant is based in an industrial zone in Changsha of Hunan Province.

In order to conduct an economic evaluation of the proposed process, the following assumptions have been made. The plant life is assumed to be 20 years, with 335 days of operation per year and 30 days shutdown for plant maintenance. During operation, the plant availability is 95%, giving a total of 7,638 working hours per year. A salvage value of 15% of the Equipment Cost (EC) is taken at the end of the project [19]. In China, the corporate tax rate is taken as 30% of the company profit, and 4.9% industrial capital loan interest rate is used. The plant construction time is 3 years [3]. The process plant was assumed to be built around an area with complete infrastructural facilities available for electricity, water and industrial sewer access. In addition, it is assumed that the prices of all products were acceptable to consumers and all the products can be sold. Concerning the governmental incentives for renewable fuels, China's tax policy currently defines that biodiesel products can be exempted from consumption tax and has a 50% reduction on the value-added tax [37, 38]. The incentives currently only apply to the consumer's side, and there have been no clear incentives for the production of biodiesel fuels.

3.2 Capital cost

The cost model is built based on the economic analysis method developed by Bridgwater et al. [39, 40]. This is the total amount of capital required to build the entire system for being ready for operation, including the costs incurred during the pre-development and construction phases. Before calculating the Total Capital Cost (TPC), the equipment cost (EC) is calculated as the total cost of purchasing new equipment delivered to the plant gate for installation. All the prices used for calculating the ECs were all selected from published data (Table 4). The calculation of Direct Plant Costs (DPC) was based on Incremental Factors including erection, instrumentation, piping and ducting, associated electrical equipment, structure and buildings, civil works and lagging. Then, the Installed Plant Cost (IPC) is calculated as the sum of management overheads and engineering design. Finally, the TPC was obtained considering the cost of commissioning, contractor's cost, interest during construction and a contingency element. Based on similar plant systems, the TPC factor is selected to be 1.69 times of DPC [39, 41].

The Annual Cost of Capital (ACC) is the annual repayment over the project lifetime, based on the assumption that the TPC is loaned at a specified interest rate at the start of the project. The ACC is calculated as:

$$ACC = TPC \times \frac{i(1+i)^n}{(1+i)^n - 1} \quad (4.)$$

where TPC is Total Capital Cost, CNY/a; n is the project lifetime in years; i is the interest rate of the capital loan.

Table 4 List of equipment and associated costs for the 5 t/h SCG valorization plant

Equipment or type of cost	Capacity	Cost (CNY)	Reference
Pre-treatment of SCG			
Weighbridge	50 t	188,597	[42]
SCG store	3,500 t	254,472	[43]
Bunker	5 t/h	479,973	[42]
Loading shovels	2 t	431,976	[42]
Excavator	2 t	431,976	[42]
Production of BD			
Compressor	440 kW	1,439,023	[3]
Heat exchanger	26.3 m^2	192,788	[3]
Fluidized bed dryer	5 t/h	2,733,454	[3]
Mixing tank	76 m^3	1,872,795	[3]
Nozzle centrifugal separator	41.2 kW	2,781,228	[3]
Evaporator	16.3 m^2	1,521,646	[3]
Liquid waste store	700 m^3	600,417	[42]
Production of AC			
Carbonization reactor	2 t/h	1,720,290	[18]
Activation reactor	2 t/h	1,703,492	[18]

Cooling system	10 m^2	57,000	[19]
Separation	22 kW	205,733	[19]
Dust-removal unit	25 kW	119,246	[19]
Fuel combustor	2950 kW	334,268	[18]
Overall			
DPC		27,821,311	
IPC		37,558,770	
TPC		47,018,016	

3.3 Operating cost

3.3.1 Consumables and Utilities

SCG is transported by lorry from the coffee processing plant to the proposed plant with an assumed nominal distance of 45 km [44]. The coffee processing plant provides the wet SCG feedstock free of charge, and it is estimated that the cost for short-distance transportation is CNY 1.2/(t•km). The costs of the raw material and utilities required for the process are calculated and presented in Table 5. The utility costs mainly consist of the costs of water and electrical power consumed. In this proposed process, the plant site, office and workshop all consume electricity. The power is supplied by the grid in order to secure the stability of the plant operation. The water usage in the plant is for BD washing and process cooling in heat exchangers.

Table 5 Process consumables and utilities costs for the 5 t/h plant

Consumables	Consumption (t/a)	Unit price (CNY/t)	Total (CNY/a)	Reference
SCG	38,190	54	2,062,260	Estimation
Hexane	45	9,840	469,767	[3]
MeOH	65.5	1,765	115,608	[45]
NaOH	10	2,211	22,110	[46]
CO_2	564	300	169,200	[47]
N_2	713	400	285,200	[48]
Total			**3,124,145**	
Utilities	Consumption (kWh/a or t/a)	Unit price (CNY/kWh or /t)	Total (CNY/a)	
Electricity	1,076,958	0.515	554,633	[49]
Water	152,760	4.1	626,316	[50]
NG	906.13	4,306	3,901,785	[51]
Total			**5,082,734**	

In 2019, the average industrial electricity price was CNY 0.515/kWh, and the average industrial water price was CNY 4.1/t in China. It is estimated that the consumption of electricity and water used for process cooling and the purification of BD and glycerol for processing 1 t of SCG are 28.2 kWh and 4 t, respectively. The NG and fuel gas (generated from the carbonization and activation process) are consumed to provide heat for the process. The NG price is taken as CNY 3.089/m^3 [51].

3.3.2 Waste disposal

The wastewater separated from raw SCG and purification of BD and glycerol is disposed of via the industrial sewers work. The cost of trade effluent discharge can be calculated by the following Eq. (5):

$$CTE = U \times \sum_{i=1}^{3} \frac{Q_i}{W_i} + (P + R) \times Q \tag{5.}$$

where U is unit pollution equivalent tax at a fee of CNY 0.7/t; Q_i is total emission of the pollutant, kg/a; W_i is the pollution equivalent value of the pollutant, kg; P is the price of industrial wastewater disposal in SCG valorization process, CNY/t; R is reception and conveyance cost for CNY 1.64/t; Q is total disposal of industrial wastewater, t.

According to Article 13 of China's Environmental Protection Law [52], the cost of the trade effluent for process wastewater discharged is CNY 8.13/t. In this work, the first three pollutants in wastewater are BD, NaOH and glycerol. Q_1, Q_2 and Q_3 are the total emissions of BD, NaOH and glycerol taken to be 28,642.5 kg, 28,298.8 kg and 19,095 kg, respectively. W_1, W_2 and W_3 are the pollution equivalent value of BD, NaOH and glycerol for 0.1 kg, 0.125 kg and 0.16 kg. P is taken to be CNY 4/t at a wastewater plant. Total disposal of industrial wastewater is calculated as 177,583.5 t. Ash produced in the carbonization and activation process is sent to landfill at a high cost of CNY 848.7/t [53].

3.3.3 Labor cost

To ensure the plant operation, a team of staff members consisting of a day team with one manager, one admin staff and one technical leader, and a rotation team with one supervisor and six operators in three shifts. The average annual labor cost for chemical plants in China is CNY 64,643 per person [54], which covers the staff wage as well as the insurance package including endowment insurance (20%), medical insurance (9.5%), unemployment insurance (1%), maternity insurance (1%), industrial injury insurance (0.5%) and housing provident fund (12%). The total annual cost of employment for the plant is calculated to be CNY 1,597,975/a.

3.3.4 Plant maintenance and overheads (M&O)

The annual cost of plant maintenance is taken to be 2.5% TPC, and the plant overheads is taken to be 2.0% TPC, both based on previous similar work [39].

3.4 Product sales

There are three products from the plant can be sold for revenue, namely BD, AC and glycerol. The base case selling price for BD is taken as CNY 4.3/kg, and the lowest and highest wholesale prices are taken as CNY 4.0/kg and CNY 4.6/kg, respectively. The base case selling price for AC is taken as CNY 7.0/kg, and the lowest and highest wholesale prices are taken as CNY 6.5/kg and CNY 7.5/kg, respectively. The selling price of glycerol is taken as CNY 5.6/kg. All prices quoted here exclude the VAT.

3.5 Minimum selling price (MSP)

The MSP covers the costs of production in the SCG valorization process, which is a reliable measure of the overall competitiveness of the project. In this work, the main products from SCG valorization are BD and AC, and the by-product is glycerol. The calculation of the MSP of BD is based on the assumption that customers purchase AC and glycerol at the minimum market price, while the calculation of the MSP of AC is based on the assumption that customers purchase BD and glycerol at the minimum market price. The MSPs of BD and AC are calculated as:

$$MSP_{\mathrm{BD}} = \frac{(ACC + OC) - S_{\mathrm{AC}} - S_{\mathrm{G}}}{Q_{\mathrm{BD}}} \tag{6.}$$

$$MSP_{\mathrm{AC}} = \frac{(ACC + OC) - S_{\mathrm{BD}} - S_{\mathrm{G}}}{Q_{\mathrm{AC}}} \tag{7.}$$

where *ACC* is the annual cost of capital, CNY/a; *OC* is the annual operating cost, CNY/a; Q_{BD} and Q_{AC} are the quantity of BD and AC respectively, kg/a; S_{BD}, S_{AC} and S_{G} is the annual sale of the BD, AC and glycerol, respectively, CNY/a.

3.6 Internal Rate of Return (IRR)

The IRR is an effective measure for the evaluation of project profitability. The IRR can be explained as the discount rate of cash flow, which makes the Net Present Value (NPV) of cash flow equal to zero. The NPV is the sum of the present values of the individual annual net cash flows. The present value is the future cash flow, which has been discounted to reflect its present value. The NPV is calculated as:

$$NPV = -C_0 + \sum_{t=1}^{T} \frac{C_{\mathrm{t}}}{(1+r)^t} + C_{\mathrm{SV}} \tag{8.}$$

where C_0 is the initial investment, CNY; *C* is the cash flow, CNY; *r* is the discount rate; *t* is the year; *T* is the project lifetime in years; C_{SV} is the present values of the salvage value of the equipment at the end of plant life, CNY.

3.7 Rate of Return on Investment (ROI)

The ROI refers to the ratio of the annual net profit (ANP) to the total invested capital (IC) of the project in a year after reaching the nominal production capacity. It is a static index to evaluate the profitability of the project, which indicates that the ANP is generated by unit investment in the normal production year. The economic significance of ROI is clear and intuitive, which reflects the advantages and disadvantages of investment to a certain extent. It can be calculated as:

$$ROI = \frac{ANP}{IC} \times 100\% \tag{9.}$$

Where *ANP* is the annual net profit, CNY; *IC* is the total invested capital, CNY.

3.8 Investment Payback Time (PBT)

The PBT is the theoretical minimum time required to recover the initial capital investment according to average profit (AP) and average depreciation (AD). AP is calculated based on revenue minus OC excluding depreciation. The initial capital investment is usually the original depreciable fixed-capital (FC), as calculated by Eq. (10):

$$PBT = \frac{FC}{(AP + AD)} \tag{10.}$$

Where *FC* is the Fixed-capital, CNY; *AP* and *AD* are the average profit and average depreciation respectively, CNY/a.

4 Results and discussion

4.1 Overall process efficiencies

Table 6 presents the process mass and energy balances and the energy efficiencies of the individual and overall SCG valorization process on the base case scenario. Fig. 2 illustrates the process mass and energy flows in the form of Sankey diagrams. The data presented in Fig. 2 employs 100.0 as the starting value for the SCG mass and energy content. The data shown was converted from the actual data presented in Table 6 in order to clearly reflect the relative percentage in each process step.

Table 6 Process mass balance, energy flow and system efficiencies

	Description	Mass (kg/h)	Energy (kW)
Feed pre-treatment			
SCG (wet)	Input to pre-treatment	5,000.0	11,375.0
DSCG	Pre-treatment product and feed to the mixing tank	1,750.0	11,375.0
Pre-treatment rejects	Waste to disposal	3,250.0	
Heat	Heat required for pre-treatment		1990.6

Oil extraction			
DSCG	Feed to mixing tank for SCG oil extraction	1,750.0	11,375.0
Hexane	Extractant for SCG oil extraction	39,375	
DFSCG	Feed to carbonization process	1,502.9	8,391.2
SCG oil	Feed to reaction tank for BD production	247.1	2,611
Heat loss	Heat released from reaction		766.8
Hexane recovery			
Hexane	Extractant for SCG oil extraction	39,375	
Hexane loss	Loss in hexane recovery	5	
Heat	Heat required for hexane recovery		4581.5
BD production			
SCG oil	Feed to reaction tank for BD production	247.1	2,217.1
MeOH	Feed to reaction tank for BD production	245.4	1,547.1
NaOH	Catalyst for transesterification	3.0	
Heat	Heat required for transesterification		413.3
BD	Main product	234.8	2,582.2
Glycerol	By-product	39.2	196.8
MeOH Recovery	Reagent recovery	221.1	1,393.9
Glycerides	Waste to disposal	0.3	2.5
Soap	Waste to disposal	0.3	2.1
Carbonization process			
DFSCG	Feed to carbonization process	1,502.9	8,391.2
Heat	Heat required for carbonization		2,138.5
Pyrolysis char	Feed input to activation process	1,188.1	8,224.1
Fuel Gas	Fuel input to gas combustor	314.9	1,296.8
Heat loss	Process heat loss		1,012.4
Activation process			
Pyrolysis char	Feed input to activation process	1,188.1	8,224.1
CO_2	Reagent for activation	369.0	
Heat	Heat required for activation		2,445.6
AC	Main product	246.0	2,288.5
Fuel gas	Fuel input to gas combustor	1052.7	7,189
Heat loss	Process heat loss		1,421.9
CO_2	Remainder reagent for emission	258.3	
Energy production			
NG	Fuel input for gas combustor	272.0	4,584.1

Fuel gas	Fuel input for gas combustor	1,367.6	8,316.1
Process wastes			
Wastewater	Waste to disposal	3,250.5	
Ash	Waste to offsite	10.9	
Process main and by products and intermediates (based on DSCG)			
SCG oil			14.1%
BD			13.4%
AC			14.1%
Glycerol			2.2%
Fuel gas			18.0%
Relative percentage of the major energy consumption units in the overall energy consumption			
Drying			17.1%
Transesterification			3.6%
Hexane recovery			39.4%
MeOH recovery			0.5%
Carbonization			18.4%
Activation			21.0%
Overall energy efficiency			
BD energy efficiency			16.2%
AC energy efficiency			14.3%
The Integrated system			30.5%

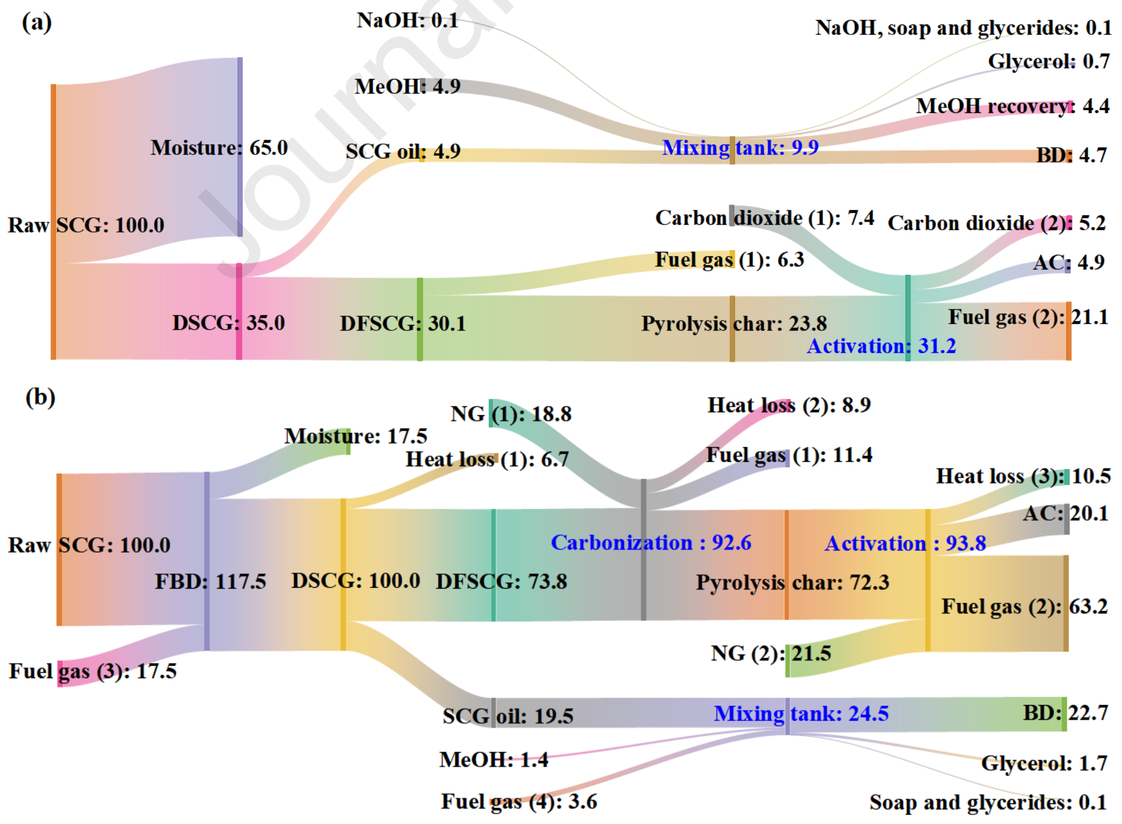

Fig. 2 Process mass balance and energy flow. (a) Mass balance (b) Energy flow

As shown in Fig. 2a, 65 wt% of the raw SCG was dried out as moisture during the pre-treatment process. For the given plant, the actual feed rate of the dry SCG is 1,750 kg/h (11,375 KW). In the oil extraction stage, 85.9% of the DSCG is converted to DFSCG with 14.1% as coffee oil. Once separated, 1,502.9 kg/h of DFSCG (8,391 kW) was fed into the carbonization and activation system for AC production and the SCG oil (247.1 kg/h, 2,217 kW) was sent into the mixing tank for BD production. Based on the conversion rate given in Table 6, the yields of main products from the process based on the mass of DSCG are: 84.5% DFSCG, 13.4% BD, 2.2% glycerol, and 14.1% AC. The rates of BD and AC production are 234.8 kg/h and 246.0 kg/h, respectively. The total energy contents of BD and AC accounted for 16.2% and 14.3% of the total energy input, respectively. The overall efficiency of the system was calculated as 30.5%. All the fuel gas (1,367.6 kg/h) was combusted on-site to generate 8,316.1 kW heat in order to meet the heat requirement for SCG drying and hexane recovery, which was 1,990.6 kW and 4,581.5 kW, respectively. The production rate of fuel gas is 1,367.6 kg/h.

It can be observed from Table 6 that the most significant energy consumption unit is hexane recovery accounting for 39.4% of the overall energy consumption. This is followed by the activation and carbonization processes accounting for 21.0% and 18.4% of the total energy consumption, respectively. During the carbonization and activation process, high temperatures (500 ℃ and 800 ℃) must be maintained to continually production of AC. In order to enhance the overall energy efficiency of the process, it would be highly important to identify a more efficient oil extraction medium that requires less energy for recovering than hexane.

4.2 MSP of the products

Fig. 3 and Fig. 4 present the calculated MSPs of BD and AC and contributions of each costing element including detailed production costs and incomes from the product sales. The positive bars represent the direct costs from the plant investment and process operation, while the negative bars indicate the incomes from AC, BD, and glycerol sales. It is assumed that both BD and AC are sold at the minimum market price. Considering all the contributing values, the MSPs of BD and AC are CNY

1.83/kg and CNY 4.42/kg, respectively. Thus, both prices are well below the market prices of BD and AC, which are CNY 4.0-4.6/kg [55] and CNY 6.5-7.5/kg, respectively [56].

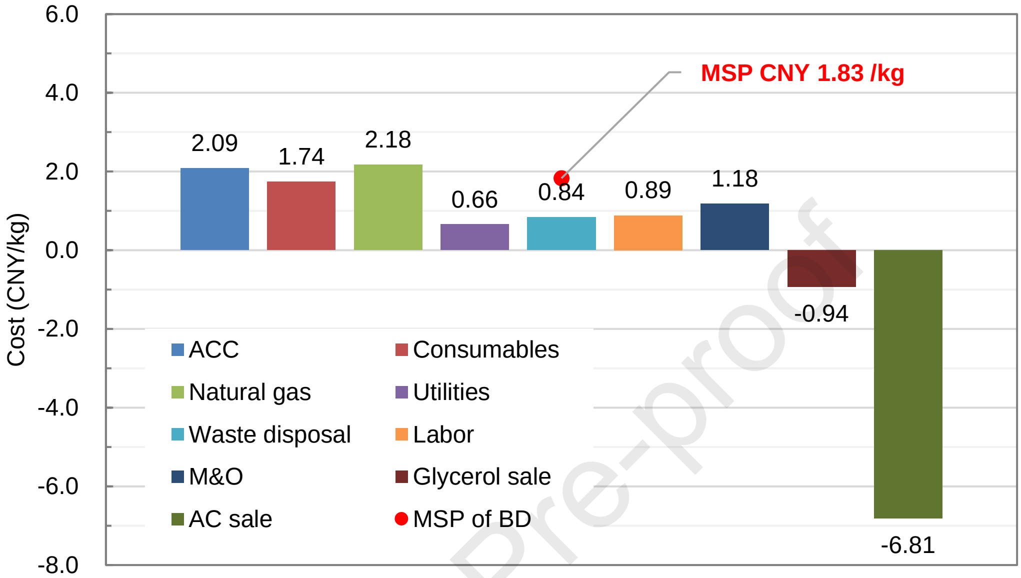

Fig. 3 The MSP of BD and its breakdown

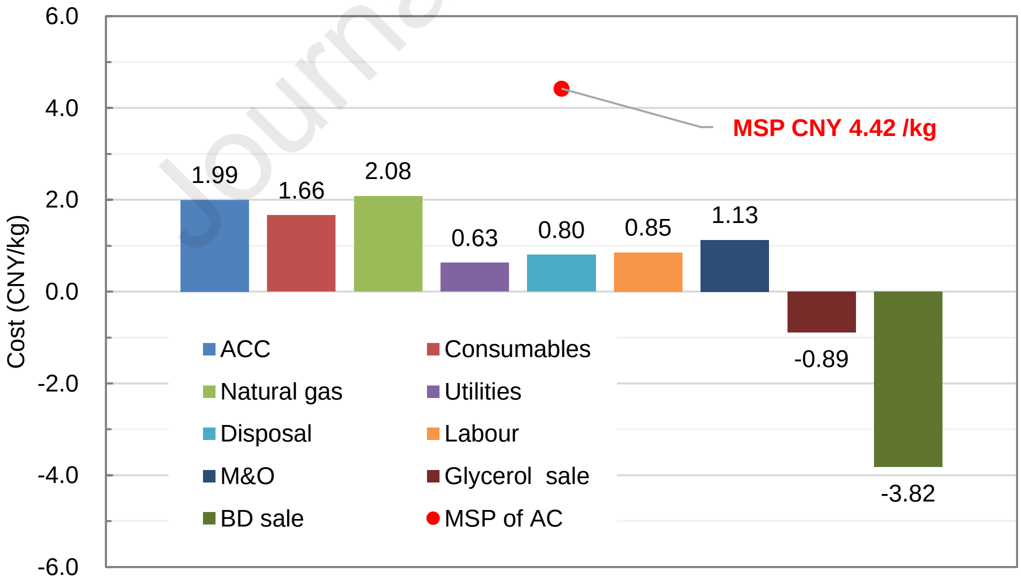

Fig. 4 MSP of AC and its breakdown

It is found that the most significant contributing factor in the MSPs of BD and AC is the cost of NG fuel, making the OC is the highest annual cost in the production costs. NG is a supplement to the pyrolysis fuel gas in this plant to provide heat for the carbonization and activation processes. Capital cost is the second-highest cost for the process. This is different from the conclusions of many similar techno-economic studies conducted in developed countries where the costs of equipment and labor are usually much higher than in China. It is also interesting to see that, in most bioenergy or biomass processing plant, the cost of material collection, storage and transportation are usually the most significant part in the operating cost. This is primarily due to the distributed location of feedstock and complicated logistic system. However, the SCG can be directly sourced from a local coffee processing plant free of charge, hence considerably reduced the associated cost in this aspect. In this study, the plant M&O, waste disposal, labor and utilities are at a similar level. Water and electricity usage account for the vast majority of utilities. The total cost of disposal consists of environmental protection tax (29%), wastewater transportation and treatment costs (66%) and the ash to landfill (5%). Although this part of the cost is relatively insignificant in the current study, it is still clear that responsibly investing in the wastewater treatment facilities on-site can reduce the potential risk for environmental pollution and improve the economic viability of the process.

In the revenue stream, the AC sales played the most critical role, as it can effectively offset the summation of capital, consumables and NG costs. The annual plant availability and selling price of BD and AC have a great influence on their MSP. Therefore, increasing the BD and AC production would further reduce the MSP of the products. It is worth noting that this work has not considered the potential government's incentive policies related to renewable fuel and energy and waste resource utilization. Based on the literature [16, 42], waste resource valorization can be potentially considered for tax exemption and additional subsidy for BD in several developed areas in China.

4.3 Internal Rate of Return, Return on Investment and Payback Time

The projection of revenues and profitability analysis is based on IRR, ROI and PBT. IRR is an important indicator for the profitability of an investment or project, especially when it comes to capital-budget decisions. The IRR was calculated based on the production cost, product sales and the net profit of the plant over the project lifetime. The project's goal is to maximize the IRR from the perspective of profitability, which means recovering the initial investment and generating enough value after the break-even point.

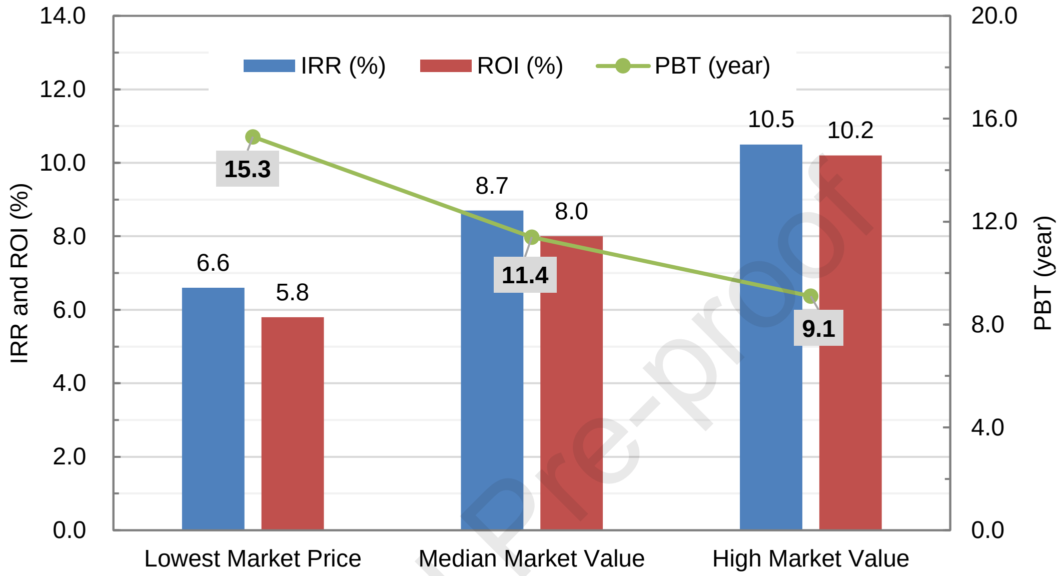

Fig. 5 Effect of BD and AC price in market on IRR, ROI and PBT

Fig. 5 presents the IRR, ROI and PBT of the proposed project when the sale prices of BD and AC are at the lowest, middle and highest price in the market in China. It is found the plant can have an IRR of 6.6%, when the BD and AC sold at low market price (CNY 4.0/kg and CNY 6.5/kg, respectively). When the BD and AC are sold at high market prices (4.6/kg and 7.5/kg, respectively), the plant can have an IRR of 10.5%. As long as the selling price is higher than the median price, the IRR would be higher than the capital interest rate (8%), confirming that the project is profitable. In general project investment, an IRR lower than 10% is hardly satisfactory and the investors usually expect an IRR of at least 25% for technology with high risk associated. Concerning the investment return, the current economic performance is possibly not highly attractive to investors.

The current plant's ROI after tax is up to 10.2% with a payback time of 9.1 years, when the selling prices of the BD and AC are at the high market price (CNY 4.6/kg and

7.5/kg, respectively). The index does not measure project performance after paying for the initial investment based on the definition. For a rule of thumb, the PBT is estimated to be between 7 and 10 years for large petrochemistry and refining plants, but the payback for high-risk processes should be much less, being 2-3 years.

These results revealed that the proposed SCG valorization plant is feasible to be implemented. When the BD and AC are sold at high market prices, it shows potentially profitable results with a slightly long PBT. Therefore, the viability of the plant heavily depends on the prices of the products.

4.4 Sensitivity analysis

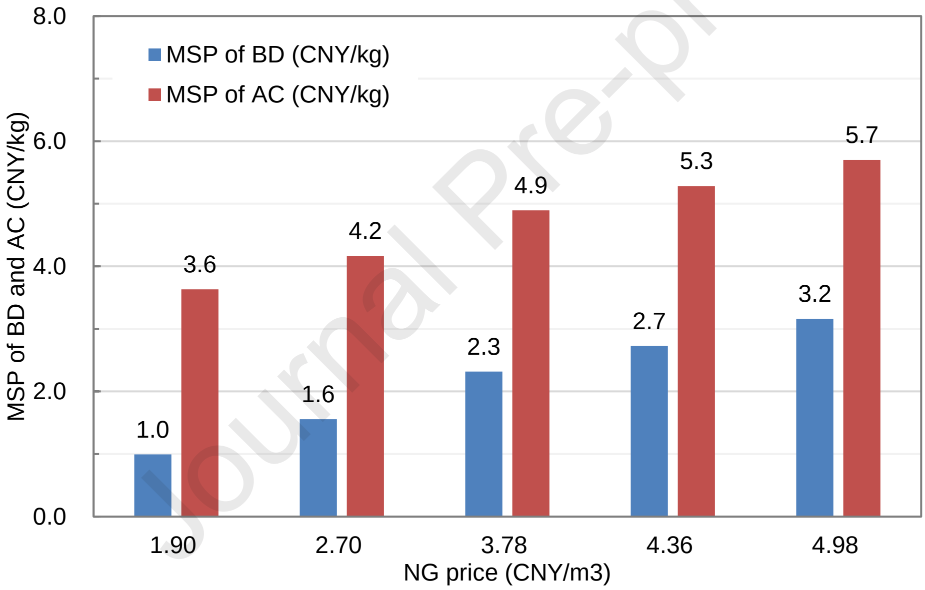

Fig. 6 Effect of NG price on the MSPs of BD and AC

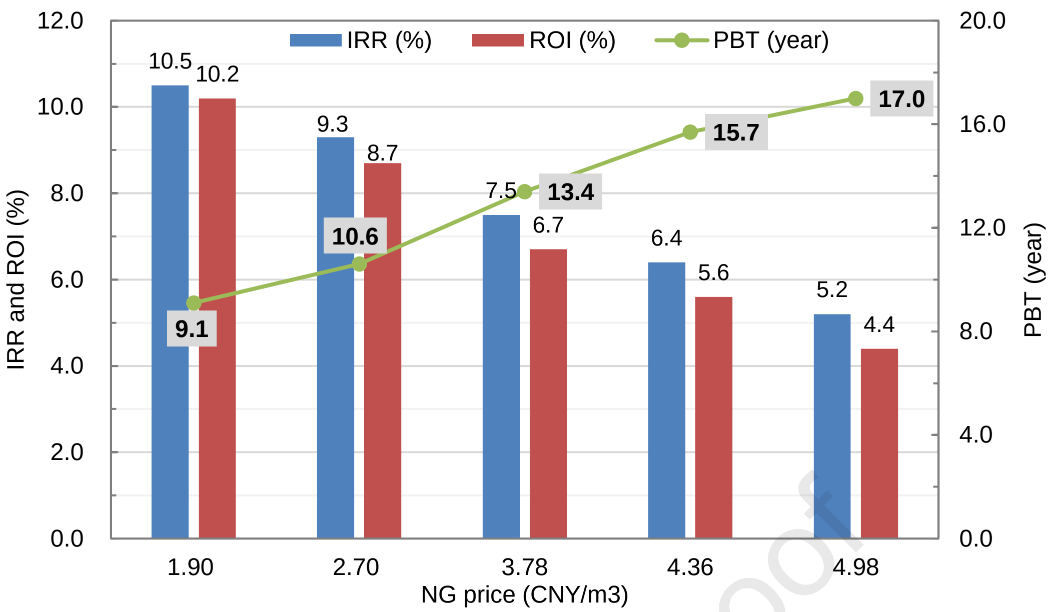

Fig. 7 Effect of NG price on IRR, ROI and PBT

The sensitivity analysis offers an in-depth understanding of the variation of different cost elements to economic performance. Fig 6 presents the impact of NG cost on the MSPs of BD and AC, and Fig 7 reveals the effect of NG cost on the economic indicators of IRR, ROI and PBT. A survey on the gas pricing in China indicates that the industrial NG price varies considerably in different regions, being CNY 1.9-4.98/m^3. The NG prices in five representative cities in China were selected for sensitivity analysis, including Xining (CNY 1.90/m^3), Shanghai (CNY 2.70/m^3), Beijing (CNY 3.78/m^3), Guangzhou (CNY 4.36/m^3) and Hangzhou (CNY 4.98/m^3). The gas pricing reflects some level of economic development but largely depends on local tax and policy. As the most significant contributing factor of the MSP, reducing the NG cost by 38.5% can lower the MSP of the BD and AC by 45.4% and 18.6%, respectively. In the meantime, it can compensate the market price of the main products and offer an IRR and PBT almost the same as those sold at high market prices (Fig 5). It is therefore of the plant operators' strong interest to optimize the process route that can more effectively utilize the process heat to reduce NG consumption, and identify suitable but low cost fuels to replace NG usage on site. It also indicated that the location is a vitally important factor in the economic performance of the plant. Xining has the lowest gas pricing among all the cities evaluated and presents the best economic performance and shortest PBT. As a relatively less developed region in Western China, the city may also offer much lower equipment, labor and other utility costs. However, the populations in these regions are also relatively less than the more developed regions, implying potentially less coffee consumption and feedstock availability. It is interesting to see that Shanghai, has a much lower gas pricing than other competitive cities like Guangzhou and Hangzhou. As the most economically vibrant city, it is likely a better location for building such plants due to low fuel cost, dense population, and excellent local incentive policies for sustainable waste processing and renewable energy.

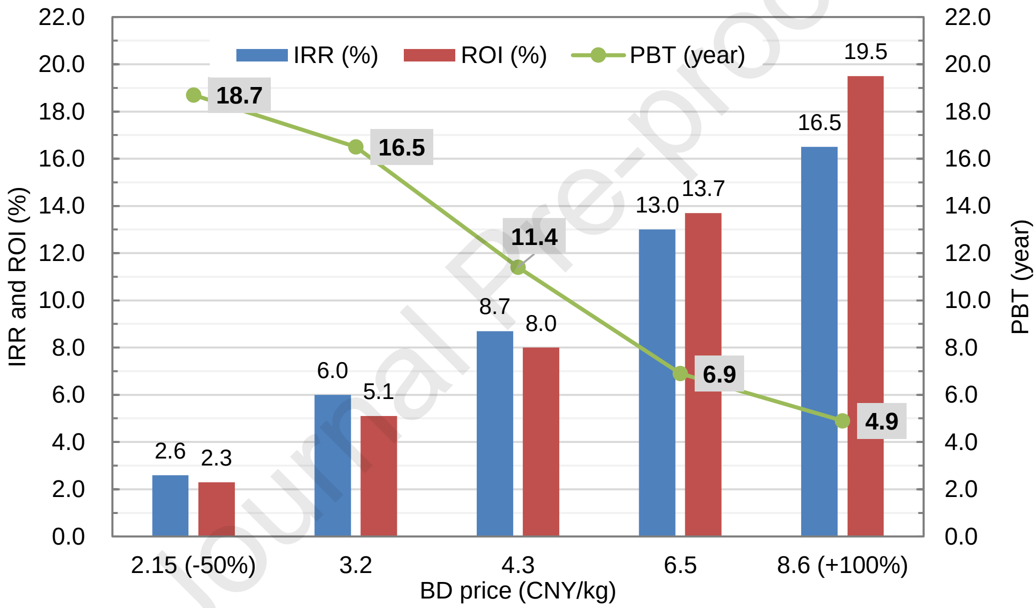

Fig. 8 Effect of BD price on IRR, ROI and PBT

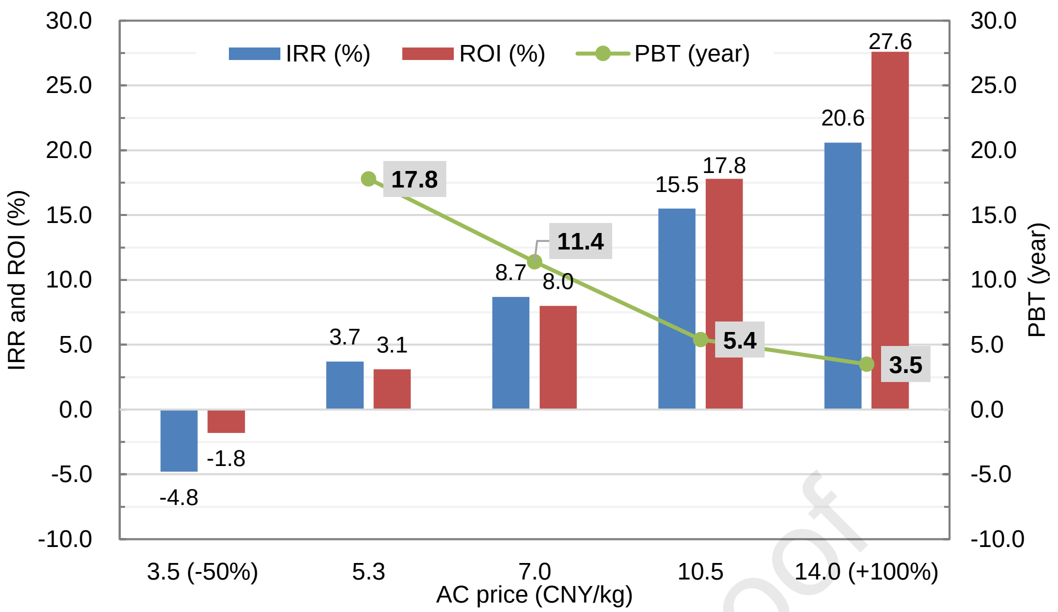

Fig. 9 Effect of AC price on IRR, ROI and PBT

Fig. 8 and Fig. 9 present the influence of individual product price variations on the performance of IRR, ROI and PBT. For BD price analysis, the selling prices of AC and glycerol are fixed as base case prices of CNY 7.0/kg and CNY 5.6/kg, respectively, while for AC price analysis, the selling prices of BD and glycerol are fixed as base case prices of CNY 4.3/kg and CNY 5.6/kg respectively. The selling prices of both products for sensitivity analysis were selected as 50%, 75%, 150% and 200% of their base case price, respectively.

From Fig. 8, if the selling price of BD can be doubled (CNY 8.6/kg), it can then give a very attractive IRR of 16.5% with a PBT of 4.9 years, comparing to an IRR of 2.6% and a PBT of 18.7 years with a pessimistic assumption of 50% price reduction. Under the current global trend of renewable energy and fuel implementation, the BD market has been experienced rapid growth and the BD price is expected to be stably increasing. Hence the pessimistic scenario of low BD prices is unlikely to happen. The same implication can be applied to the AD price as the material is produced from waste rather than conventional fossil resources. From Fig. 9, it can be clearly seen that a 50% reduction in AC selling price (CNY 3.5/kg) can result in a negative IRR of -4.8%, which means that the process would bring a loss of present value. As the selling price of AC was doubled as CNY 14.0/kg, the IRR can be sharply increased to over 20% with a PBT as short as 3.5 years. This implies that further process development should be driven towards developing high-quality functional AC materials that can attract high market values.

Some previous studies indicated that the profitability and sustainability of this type of plant favored high production capacity and the process economics of BD and AC manufacturing tended to be more feedstock dependent than process dependent [15-17]. These indicate that increasing the raw material processing capacity and BD and AC production capacity is the key to improving plant economics. Moreover, the plant owner should seek to arrange sufficient and competitive selling contracts with relevant customers and wholesalers in order to established network distribution into full play.

5. Conclusions

This work presented the integration of SCG valorization process for biodiesel and activated carbon co-production, and comprehensively evaluated the process energy utilization and its techno-economic performance in China's context. According to the process analysis on a wet feedstock basis, the current SCG valorization plant can produce 1,793 tons of biodiesel, 1,879 tons of activated carbon and 299 tons of glycerol per year with product yields of 13.41%, 14.06% and 2.24%, respectively. The overall SCG valorization process efficiency is 30.5%. The fuel gas produced from the pyrolysis process can be used for process heat generation, but additional natural gas is required in order to fully meet the heat demand of the process. Significant energy consumption occurs in hexane recovery, activation and carbonization process subsystems, which account for 39.4%, 21.0% and 18.4% of the total energy consumption, respectively.

From the economic analysis, the base case MSPs of BD and AC are calculated to be CNY 1.83/kg and 4.42/kg, respectively, which are well below the current market prices of these products. The breakdown of the production cost indicated that the cost of gas has the most significant impact on the MSP, following by the costs of annual capital and process consumables. If the products can only be sold at low market prices, the process can be marginally profitable with an IRR of 6.6% and a payback of 15.3

years. When the products are sold at high market prices, the IRR can be reduced to 10.5% with a payback of 9.1 years. Sensitivity analysis indicated that it is essential to identify locations with low fuel and consumables costs and favorable incentive policies. Technology developers should seek to enhance the function and quality of the products to improve the market value of the products to enhance economic viability.

For future work, attention would be paid to a comprehensive evaluation of more key variable parameters that can also affect the plant's technical performance and economic viability. These include the feedstock processing capacity, availability and the production capacity of BD and AC, which all have considerable impacts on the process and operation. Attempts could also be made to incorporate the commercial modelling tools (such as Aspen Plus) into this classic spreadsheet model to enhance the process model's reliability and accuracy. In addition, it is equally important to evaluate the plant's sustainability, environmental impacts and socioeconomic implications from a life cycle perspective in order to fully reflect the benefits of the technology.

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Appendix

Nomenclatures

η_{BD}	Biodiesel efficiency	AC	Activated carbon
η_{AC}	Activated carbon efficiency	ACC	Annual Cost of Capital
C_0	Initial investment	AD	Average depreciation
C	Cash flow	ANP	Annual net profit
C_{SV}	Present values of the equipment salvage value	AP	Average profit
E_{BD}	Power outputs of biodiesel	BD	Biodiesel
E_{AC}	Power outputs of activated carbon	CEPCI	Chemical Engineering Plant Cost Index
E_{SCG}	Energy contents of spent coffee grounds	CTE	Cost of trade effluent
E_{NG}	Energy contents of natural gas	DSCG	Dried spent coffee grounds
E	Emission of this pollutant	DFSCG	Defatted spent coffee grounds
i	Interest rate of the capital loan	DPC	Direct Plant Costs
n	Project lifetime in years	EC	Equipment Cost
P	Price of industrial wastewater disposal	EI	Chemical Engineering Economic Indicators
Q	Total disposal of industrial wastewater	FC	Fixed-capital
Q_{BD}	Quantity of biodiesel	IRR	Internal Rate of Return
Q_{AC}	Quantity of activated carbon	IPC	Installed Plant Cost
Q_i	Total emission of the pollutant	IC	Invested capital
R	Reception and conveyance cost	M&O	Maintenance and overheads
r	Discount rate	MSP	Minimum selling price
S_{BD}	Sale of the biodiesel	NPV	Net Present Value
S_{AC}	Sale of activated carbon	NG	Natural gas
S_G	Sale of glycerol	OC	Operating Cost
T	Project lifetime	PBT	Payback Time
t	Year	ROI	Return on Investment
U	Unit pollution equivalent tax	SCG	Spent coffee grounds
W_i	Pollution equivalent value of the pollutant	TPC	Total Capital Cost

SCG was processed for co-production of biodiesel and activated carbon.

The yields of BD and AC on a wet feed basis are 13.41% and 14.06%, respectively.

The MSPs of BD and AC are lower than market prices, making the process profitable.

The overall efficiency of the integrated system is calculated to be 30.5%.

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: