ELSEVIER

Chemical Engineering Journal 109 (2005) 147–165

Chemical Engineering Journal

www.elsevier.com/locate/cej

Production of activated carbon from bamboo scaffolding waste—process design, evaluation and sensitivity analysis

Keith K.H. Choy, John P. Barford, Gordon McKay *

Department of Chemical Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong SAR, China

Received 5 January 2005; received in revised form 21 January 2005; accepted 15 February 2005

Abstract

A feasibility study has been carried out on the preliminary process design of the production of activated carbon from the bamboo scaffolding waste based on 30 tonnes of bamboo waste per day throughput. A comparison of the process economics of the stand-alone bamboo carbonization plant with a plant that is integrated into another major processing facility has been studied. The preliminary process design was based on various literature sources and an economic evaluation, in which the total capital investment (TCI), the production cost, the return on investment (ROI), the cash flow and the internal rate of return (IRR) of the stand-alone plant and integrated plant were estimated. The TCI of the stand-alone plant and integrated plant are HK$ 7,430,000 and HK$ 6,430,000, respectively. Net present values of two plants at various discount factors have been determined and the IRR have been estimated as 13.0 and 20.1% for the stand-alone plant and integrated plant, respectively. Sensitivity analysis reveals that the cash flow of the project would be increased or decreased up to 40, 65 and 120% by varying production factors of cost of chemical activation agent, production capacity and selling price of activated carbon, respectively, in the extent of ±25%.

Keywords: Bamboo scaffolding waste; Activated carbon; Process design; Economic evaluation

1. Introduction

Bamboo is a tropical plant and is common in Southern Asia such as China [1], Thailand and Vietnam [2]. It can grow very fast, 120 cm in 24 h [3], and consume energy of 0.5 MJ/kg only during the growth comparing to 0.8 and 30 MJ/kg for timber and steel [4]. Proximate and elemental analyses of one kind of Indian bamboo are shown in Table 1 (Technology Information, Forecasting and Assessment Council, India).

Bamboo cane, indigenous to Hong Kong and China is available as scaffolding waste from Hong Kong construction projects. Over 50,000 tonnes of bamboo scaffolding waste each year is dumped as construction waste. Bamboo scaffolding is economical (US$ 1.29 per 6 m bamboo pole), flexible (to cut a desired length) and efficient (erecting is easy) [2] in construction. Three types of bamboo imported mainly from Southern China are using for construction in Hong Kong, namely, Bambusa Pervariabius, Phyllostachys and Pubescensand Fir [5]. People also use it for signage, slope and demolition works. However, bamboo pole has a finite life span due to its weakening and degradation. As Hong Kong has a high frequency of construction and repair works, consequently, a lot of bamboo wastes were disposal into landfilling site each year. In 1992, the percentage of bamboo waste out of total construction waste was 0.4% [6].

Bamboo waste can be used as a raw material for the production of a range carbon chars and activated carbons due to its high carbon content shown in Table 1. The bamboo cane can be carbonized/charred in a furnace at high temperature in the absence of oxygen to produce carbon chars. The chars can be treated using various chemicals and over a range of temperatures to produce a selection of activated carbons for various uses [7–9]. Bamboo-based activated carbons can be expected to find uses as: (1) a potential commercially available activated carbon for the treatment of gaseous pollutants and (2) a potential commercially available activated carbon for the treatment of liquid pollutants in industrial effluents and in drinking water filtration applications.

* Corresponding author. Tel.: +852 2358 8412/7133; fax: +852 2358 0054.
E-mail address: kemckayg@ust.hk (G. McKay).

1385-8947/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.cej.2005.02.030

Table 1
Proximate and elemental analyses of one kind of Indian bamboo

	Proximate analysis (dry basis (%))			Elemental analysis (%)			
	Volatiles	Fixed	Ash	Carbon	Hydrogen	Nitrogen	Sulfur
Bamboo	80.6	15.6	3.9	43.8	6.6	0.4	Nil

The use of waste bamboo scaffolding from the construction industry will be a valuable outlet for one of Hong Kong's waste products. In addition, many industries in Hong Kong (textiles, clothing, microelectronics, electroplating, chemical, food, drink, petrochemical) have problems finding an economically feasible method of removing pollutants from effluents. The development of activated carbons in Hong Kong will be a tremendous incentive for local industries to utilize these materials. It will also give industry a chance to recover, recycle and re-use these pollutants, which in most cases are valuable raw materials/intermediates or products of their processing operations. This project is specifically targeted at potential future uses in Hong Kong. Currently the Hong Kong SAR Government is looking at a number of options to reduce wastes (MSW, sewage sludge, hazardous chemical wastes) by incineration projects. It is well established that such incineration processes produce dioxins which can be most effectively removed by adsorption onto activated carbons—a usage of 50–100 tonnes/day.

2. Bamboo characteristics

2.1. Bamboo as raw material for activated carbon

The choice of raw material has an important impact on the economy of producing activated carbon. Typical raw materials used for the preparation of activated carbon include coal [10], bone char, lignite and agricultural by-products such as coconut shells [11,12], bagasse [13], rice hulls [14], peach stones [15]. The criteria used when choosing a carbonaceous raw material includes potential for obtaining high quality activated carbon low inorganic content, volume and cost of the raw material, workability of the raw material, minimum environmental impact, and storage life of the raw material.

The basis of this project is to utilize Hong Kong bamboo construction scaffolding waste as a raw material to produce activated carbon since it is cheap, even no cost. In Hong Kong, approximately 50,000 tonnes of bamboo scaffolding waste per year is dumped as construction waste. It has most of the desired properties for a good raw material and does not have the environmental impacts of using petroleum coke and wood, as it is a waste material. A literature survey has recently been carried out to investigate which raw materials have been used for activated carbon production but no references mentioned bamboo as a raw material. Current commercial processes use coal, bagasses, coconut shell, peat, lignite and wood.

2.2. Chemical properties of bamboo cane

Information on the chemical composition of the components that constitute bamboo is important in evaluating alternative processing and recovery options. The feasibility of carbonization depends on the chemical composition of the bamboo. Determining the elemental composition of bamboo by elemental analysis is a key factor for the detailed design of the production of activated carbon from a bamboo carbonization plant and helps confirm the accuracy of material and energy balances of the bamboo carbonization process. The ultimate analysis of a bamboo component typically involves the determination of the percent of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulfur (S) and ash. Because of the concerns over the emission of chlorinated compounds, e.g. dioxins, during combustion, the determination of halogens is often included in an ultimate analysis. The results of the elemental analysis are used to characterize the chemical composition of the organic matter in bamboo.

The average chemical composition of bamboo is measured by an elemental analysis and is shown in Fig. 1. The major elements are carbon (47.6%) and oxygen (43.9%) accounting for around 91% of bamboo. Other elements include hydrogen (6.5%), nitrogen (0.3%), sulfur (0.3%) and ash (1.4%). The ash content of the bamboo is determined by a thermogravimetric analysis (TGA), the TGA will be discussed later. The results are very close to the finding by Technology Information, Forecasting and Assessment Council, India (see Table 1). A more detailed chemical composition of bamboo must be determined on different types of Hong Kong bamboo in future if the feasibility study of the bamboo carbonization process is to proceed.

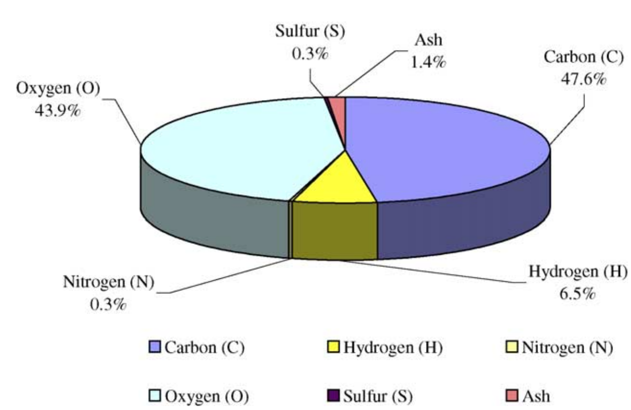

Fig. 1. Elemental composition of bamboo cane.

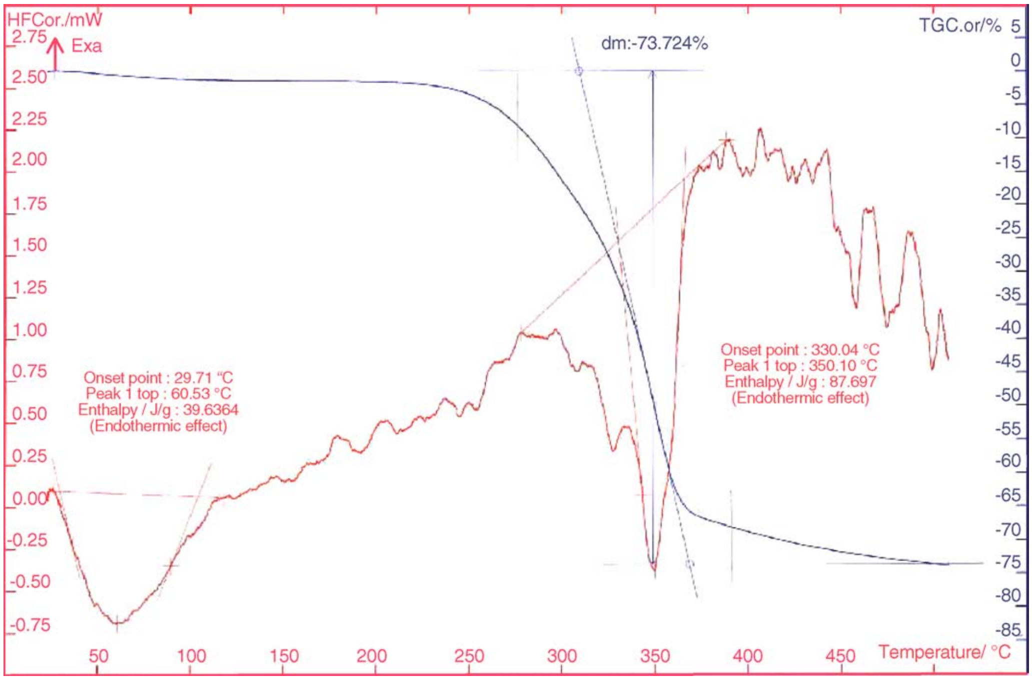

Fig. 2. Differential thermogram of bamboo in the absence of oxygen.

2.3. Heat of carbonization for bamboo

After estimating the elemental composition of the bamboo, the heat of carbonization of bamboo must be determined in order to perform a calculation of the material and energy balances for the bamboo carbonization process. The heat of carbonization can be found by using a differential thermal analysis (DTA). In DTA, the heat absorbed or emitted by a chemical system is observed by measuring the temperature difference between the system and an inert reference compound as the temperatures of both are increased at a constant rate.

Fig. 2 is a differential thermogram obtained by heating the bamboo in a flowing stream of nitrogen (absence of oxygen), similar to the bamboo carbonization process, it was found that the bamboo carbonization process starts at around 250 °C and

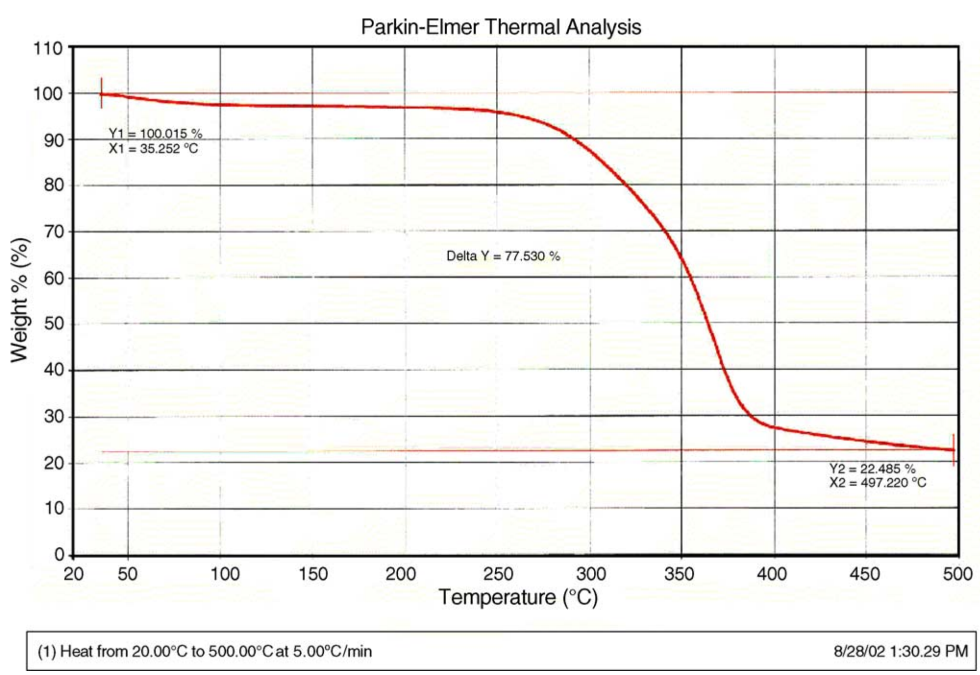

Fig. 3. Thermogram for carbonization of bamboo.

obtains a minima termed peak (350 °C) in which accounts for more than 70% weight loss of bamboo during the process. The minima indicate that the bamboo carbonization process is an endothermic reaction and the heat of carbonization of bamboo is 87.70 J/g. The specific heat of carbonization of bamboo at different conditions (under chemical activation or different temperatures) will be determined if this study is to proceed in more detail in the future.

2.4. Yield of the bamboo carbonization process

The yield of activated carbon from the bamboo carbonization process can be determined by using a thermogravimetric analysis (TGA). In a thermogravimetric analysis, the mass of sample is recorded continuously as its temperature is increased linearly from ambient to as high as 1200 °C. A plot of mass as a function of temperature (a thermogram) provides both qualitative and quantitative information. Fig. 3 is a recorded thermogram obtained by increasing the temperature of bamboo in a flowing stream of nitrogen (absence of oxygen) at 5 °C/min. The significant weight change of bamboo starts at 240 °C (same as DTA results) and stops at 500 °C, hence, the yield of bamboo carbonization is approximately equal to 22.5%. The thermogravimetric analysis (TGA) can also be used to determine the ash content of the bamboo in which the bamboo is heated up in a flowing stream of air.

3. Process design for bamboo carbonization plant

3.1. Process description for stand-alone plant

The current bamboo carbonization plant is designed to carbonize 30 tonnes of bamboo per day to produce activated carbon. The process flow diagram is shown in Fig. 4. The raw material, bamboo, will be crushed and blended into a smaller particle size in order to facilitate the carbonization thereafter. Then, the granular bamboo will be impregnated with the potassium hydroxide (KOH) solution for chemical activation which is then evaporated at 110 °C in an oven for 8 h to remove water and the potassium hydroxide addition is 70 wt.%. The alkaline treated bamboo is then transferred to a carbonization furnace through a conveyor. The carbonization furnace is operating at 850 °C in the absence of air. Nitrogen is used to purge the carbonization furnace to provide an oxygen-free environment for the carbonization reaction to take place.

Volatile gases, usually consisting of carbon dioxide, carbon monoxide, hydrogen, methane and some light hydrocarbons, will leave the carbonization furnace together with the nitrogen gas in the gas stream. These volatile gases are a high-energy content fuel gas and part of the energy fuel gas is used as fuel for combustion to provide heat in the carbonization furnace and oven. According to the experimental results in a laboratory, the overall yield of the activated carbon from the bamboo carbonization process is around 20–24% and the production rate of the activated carbon is around 6.6 tonnes/day in this process. The resultant product, activated carbon, after cooling in an inert atmosphere will be washed with water to remove and recover the impregnant (KOH) and is then dried in a furnace. The recovered KOH is used to impregnate the new batch of bamboo in the chemical activation process again. The activated carbon formed will be delivered through a conveyor in an activated carbon storage tank for packaging and delivery.

The rest of the volatile gases generated from the carbonization furnace are then fed to the combustion chamber mixing with an air for final combustion. The temperature of combustion chamber is maintained at a high combustion temperature (around 1000 °C) with a residence time of not less than 2.5 s to reduce the formation of NO_x. The outlet temperature of the combustion chamber is high so that harmful materials such as dioxin are destroyed. Following the combustion chamber the flue gas is led into a cyclone for complete combustion. The particles are separated out, collected and discharged at the bottom of the cyclone.

The hot flue gas coming out from the cyclone at around 1000 °C flows to a steam boiler for energy recovery; and electricity is generated by a steam turbine. Then, a heat exchanger is used to produce hot water from the remaining heat. The steam turbine and heat exchanger system are designed to cool down the flue gas to around 170–200 °C. The driving force of the gas flow through the combustion chamber and the energy recovery system is a slight suction-pressure created by the flue gas fan. Flue gas coming out from the heat exchanger will then enter a lime scrubber unit for HCl and SO_x removal. The tail gas is then sent to the stack after removing fly ash and fine particles using a bag-house filter system. A continuous-emission-monitoring (CEM) unit is installed at the end of the pipe to ensure the quality of the gas emission does not exceed the government set limits by the Hong Kong Environmental Protection Department, HK-EPD (see Table 2). The equipment list of the stand-alone bamboo carbonization process is shown in Table 3.

3.2. Process description for integrated plant

In this case the overall process works in exactly the same way as the process in the stand-alone plant except that the environmental emission treatment equipment is not required. If the bamboo carbonization process plant is integrated into another major (or much larger) processing facility, such as

Table 2
Stack emission limit of Hong Kong

Species	HK-EPD half-hourly emission limit (mg/m^3)	Stack emission (mg/m^3)
SO_2	200	113.7
NO	400	122.6
Particulates	30	1.4

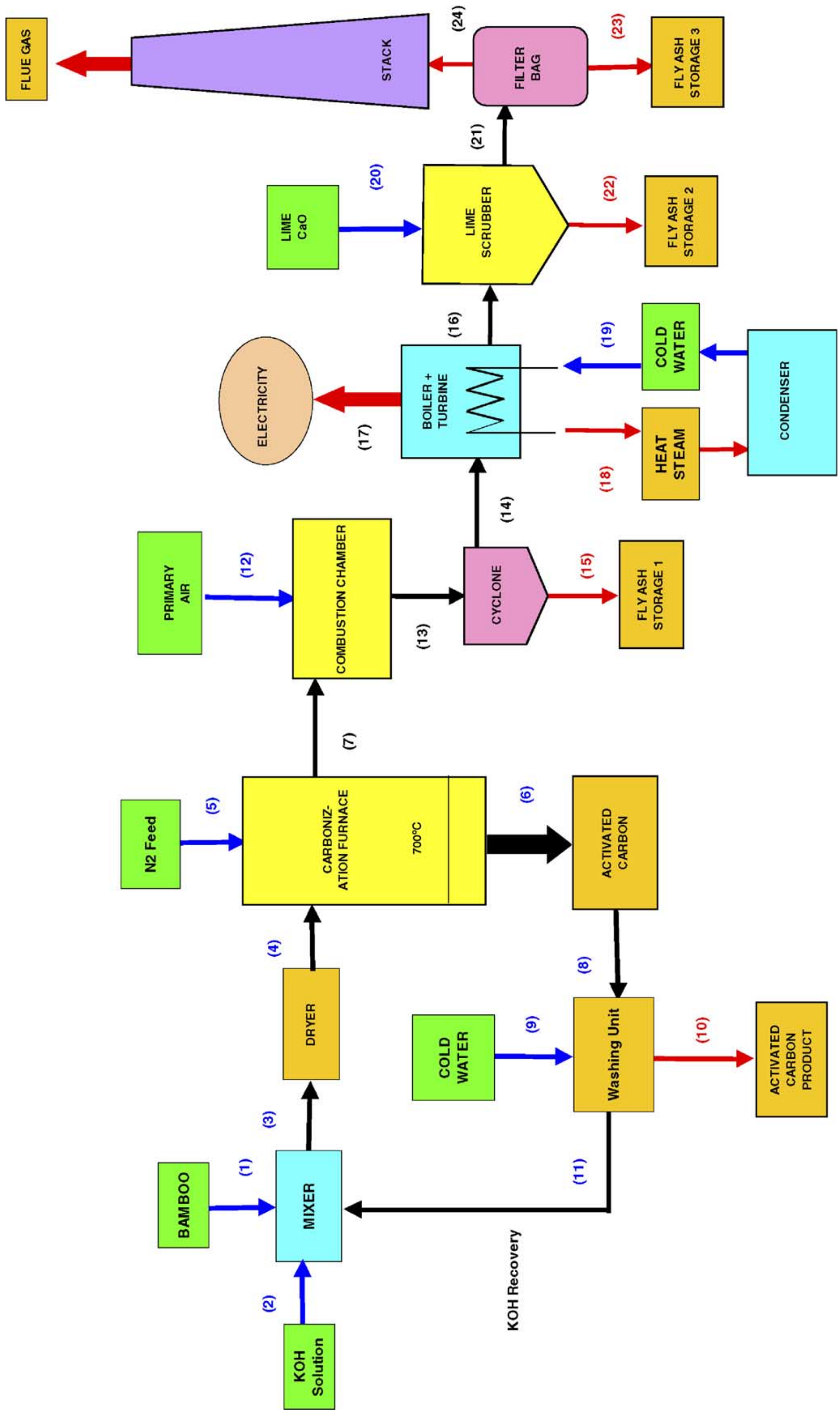

Fig. 4. Process flow diagram.

Table 3
Major equipment items in the production of activated carbon from bamboo carbonization process

Item no.	Item description	Sizing parameter	Temperature (K)
E-101	Carbonization furnace	1.88 Mbtu/h	973
E-102	Bamboo dryer × 3	10 tonnes/day	383
E-103	Activated carbon dryer	7 tonnes/day	383
E-104	Crusher	2 tonnes/h	293
E-105	Nitrogen storage tank	1.92 m^3	196
E-105	Mixing tank	10 m^3	293
E-201	Combustion chamber	42297 m^3/h	1499
E-202	Primary air blower	7591 m^3/h	298
E-203	Carbon washing tank	10 m^3	973
E-204	Activated carbon storage tank	137 m^3	973
E-301	Cyclone	42135 m^3/h	1493
E-302	Fly ash container (1)	5 m^3	1493
E-401	Steam boiler packed	3781 kg/h	1487
E-402	Steam turbine	337 kW	673
E-403	Condenser	4 m^2 area	473
E-404	Deionization columns	3781 kg/h	293
E-405	Regeneration system	3781 kg/h	293
E-501	Scrubber	12501 m^3/h	473
E-502	Fly ash container (2)	1 m^3	473
E-503	Lime feeder	0.4–14 kg/h	293
E-504	Lime storage tank	1 m^3	293
E-601	Filter bag house	12455 m^3/h	443
E-602	Fly ash container (3)	1 m^3	443
E-701	Ash quenching tank system	Packaged	873
E-702	Wastewater treatment system	22 m^3/day	293
E-801	Packaging unit	Packaged	293
E-802	Conveyor × 5 (100 ft)	2 tonnes/h	773
E-901	Stack	0.33 m × 50 m	443

one of the following:

1. a thermal electricity generating facility;
2. a cement manufacturing facility;
3. a thermal hazardous waste processing plant;

then these companies will already have the required environmental treatment trains of process equipment required for SO_x, NO_x reduction. Therefore, these additional items (if already available on the large scale treatment plants) will not be necessary and will reduce the capital costs of the bamboo processing facility. The items not required in the integrated plant are shown in Table 4. These results in net plant equipment will save of US$ 158,674, and a saving in total capital investment (see chapter 6) of US$ 1,000,260.

Table 4
Equipment items not necessary for integrated bamboo carbonization plant

Item name	Item number
E-501	Scrubber
E-502	Fly ash container (2)
E-503	Lime feeder
E-504	Lime storage tank
E-601	Filter bag house
E-602	Fly ash container (3)
E-701	Ash quenching tank system
E-702	Wastewater treatment system
E-901	Stack

4. Results and discussion

4.1. Process simulation

In order to carry out the costing and economic evaluation of the production of activated carbon from bamboo, a material and energy balance calculation of the bamboo carbonization process must be done before. Microsoft Excel is chosen as the software to simulate the whole bamboo carbonization process in order to find out all the information required in the economic evaluation such as the production rate of activated carbon, the sizing parameter of each operating units, temperature of the process, heat energy (fuel) required in the furnace system, amount of the utilities (water, nitrogen), etc. The basic principle for both material and energy balance is simply based on the following equation:

$$\text{Input} + \text{Generation} = \text{Output} + \text{Consumption} + \text{Accumulation}$$

In all the mass balance calculations, no mass accumulation in the design process is assumed. Since the mass balance involved reaction, it is calculated by using the mole flow of each compound when reaction is involved in the process. Each reaction depends on the conversion of reaction since all the reactions are assumed in equilibrium and the number of moles consumed in the reaction is equal to the number of generated in the process. In mole basis, the relation becomes

$$\sum (F_i)_{\text{input}} + \sum (F_i)_{\text{generation}} = \sum (F_i)_{\text{output}} + \sum (F_i)_{\text{consumption}}$$

where F_i = molar flowrate of species i (kmol/h).

In an open system, mass is allowed to cross the system boundary as the process occurs, the energy is usually governed by the following balance equation:

$$Q + \left[\sum F_i \int_{T_R}^{T} C_{p_i}\, dT\right]_{\text{in}} - \left[\sum F_i \int_{T_R}^{T} C_{p_i}\right]_{\text{out}} - F_i \Delta H_{\text{RX}}(T) = 0$$

4.2. Laboratory scale production on activated carbon from bamboo

A series of laboratory works were conducted to determine the relationship between experimental conditions and the yield as well as properties of bamboo carbon. The bamboo cane for experiment was shredded to a nominal size of 5 mm. The granular bamboo will be impregnated with the KOH solution (70 wt.%) for chemical activation which is then evaporated at 110 °C in an oven for 24 h to remove water.

After impregnating the bamboo cane, pre-weighed sample was then placed in a muffle furnace. Nitrogen was then introduced into the furnace at a rate of 200 cm^3/min. The sample was activated at 850 °C in the absence of oxygen for 2 h. The resulting activated carbon was cooled under nitrogen and then was rinsed and stirred with deionized water to recover the KOH until the water rinsed out had an approximate pH value of 8. The rinsed activated carbon was dried in an oven at 110 °C for 24 h and kept for further characterization such as BET surface area. It was found that the yield of this bamboo carbonization process is around 22% and carbons generated under these conditions yield product with high surface area up to 800 m^2/g.

4.3. Economic evaluation of the stone-alone and integrated bamboo carbonization plant

The aim of this section is to present information regarding the economic feasibility for the production of activated carbon from bamboo construction waste. The technical feasibility and the process routes have been established and outlined in the previous sections. For the purpose of this economic study, the mass balance information presented in the process simulation section has been used in this study. This economic evaluation is based on the carbonization of 30 tonnes bamboo per day, the rate of production of activated carbon is around 6.6 tonnes and 300 kW of electricity will be generated by the bamboo carbonization process. The costing for this study is based on a standard factored estimate procedure; such estimates are typically accurate to within ±25% of the final cost of the plant. The complete cost estimation of the plant is included into two main parts—total capital investment and production cost. A detailed breakdown of each part is given in the following sections.

4.3.1. Total capital investment

Before a plant can be put into operation, a large sum of money must be supplied to purchase and install the necessary machinery and equipment. Land costs and service facilities must be obtained, and the plant must be erected complete with all piping, controls, and services. In addition, it is necessary to have money available for the payment of expenses involved in the plant operation. The capital needed to supply the necessary manufacturing and plant facilities is called the fixed capital investment and includes direct and indirect costs, while that necessary for the operation of the plant, in the initial phase, is termed the working capital. The sum of the fixed capital investment and the working capital is known as the total capital investment. The total capital investment is determined by factorial method in this report. The following simple tree diagram (Fig. 5) can represent the calculation.

4.3.1.1. Costing for the major plant items. This section lists the major plant items that are required for the process and explains the techniques involved in sizing and costing of these major equipment items. Table 5 shows the major equipment items and the cost of those items which are required for this plant. Most cost information was provided and obtained by Matches Company, A Guide to Chemical Engineering Process Design and Economics [16], Coulson and Richardson's Chemical Engineering Volume 6 [17] and Plant Design and Economics for Chemical Engineers [18]. The expected error into the factored costing estimation is ±20–30%. The cost obtained from the references may not be the latest equipment cost. Thus, the equipment cost can be updated by using the Marshall and Swift Index [19]:

$$\text{Cost of plant item}\,(2003) = \text{Cost of plant item}\,(19XY) \times \left[\frac{\text{cost index 2003}}{\text{cost index }19XY}\right]$$

From Table 5, the total cost of the major plant equipment items is US$ 1,193,273. We have assumed an additional fac-

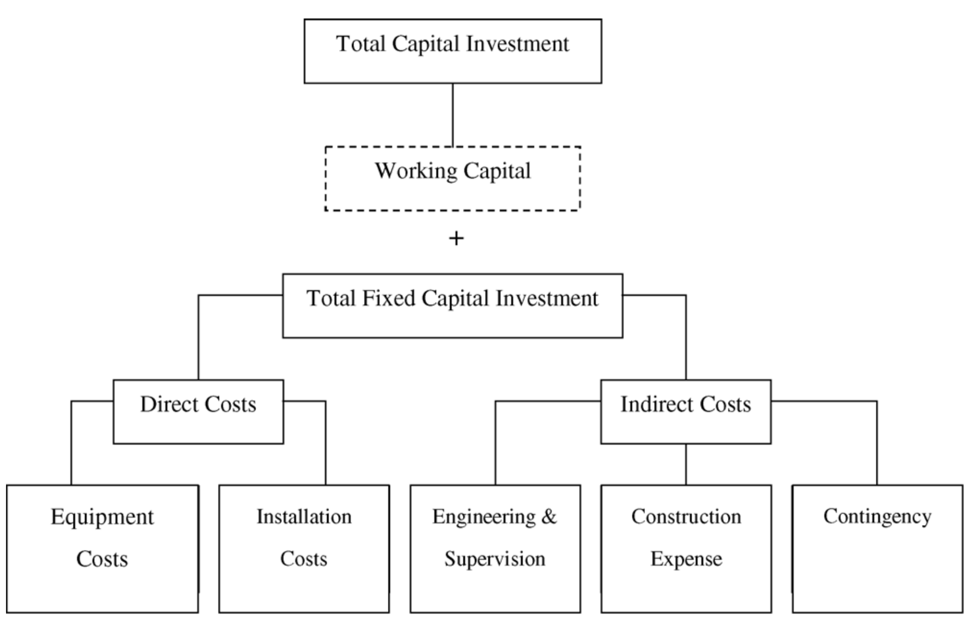

Fig. 5. Simple tree diagram for total capital investment determination.

Table 5
The major items of equipment and their costs involved in the production of activated carbon from bamboo carbonization process

Item no.	Item description	Sizing parameter	Design temperature (K)	Design pressure (atm)	Material of construction	Basic unit cost (US$)	Year	Unit cost US$ (2002)
E-101	Carbonization furnace	1.880 Mbtu/h	973	1.2	Carbon steel	130115	2002	130115
E-102	Bamboo dryer × 3	10 tonnes/day	383	1.2	Carbon steel	16400	2000	51266
E-103	Activated carbon dryer	7 tonnes/day	383	1.2	Carbon steel	12752	2000	39862
E-104	Crusher	2 tonnes/h	293	1.2	Carbon steel	35000	1990	44940
E-105	Nitrogen storage tank	1.92 m^3	196	1.2	Carbon steel	15000	1990	19260
E-105	Mixing tank	10 m^3	293	1.2	Carbon steel	11000	1990	14124
E-201	Combustion chamber	42297 m^3/h	1499	1.2	Carbon steel	69199	2002	71064
E-202	Primary air blower	7591 m^3/h	298	1.2	Carbon steel	6828	2002	6828
E-203	Carbon washing tank	10 m^3	973	1.2	Carbon steel	11000	1990	14124
E-204	Activated carbon storage tank	137 m^3	973	1.2	Carbon steel	50000	1990	64200
E-301	Cyclone	42135 m^3/h	1493	1.2	Carbon steel	29129	2002	29129
E-302	Fly ash container (1)	5 m^3	1493	1.2	Carbon steel	7000	1990	8988
E-401	Steam boiler packed	3781 kg/h	1487	45	Carbon steel	100626	1999	103338
E-402	Steam turbine	337 kW	673	45	Carbon steel	201252	1999	206677
E-403	Condenser	4 m^2 area	473	1.2	Carbon steel	9500	2002	9500
E-404	Deionization columns	3781 kg/h	293	1.2	Plastic	27118	2002	27118
E-405	Regeneration system	3781 kg/h	293	1.2	Plastic	27118	2002	27118
E-501	Scrubber	12501 m^3/h	473	1.2	Carbon steel	6948	2002	6948
E-502	Fly ash container (2)	1 m^3	473	1.2	Carbon steel	3000	1990	3852
E-503	Lime feeder	0.4–14 kg/h	293	1.2	Carbon steel	7000	2002	7000
E-605	Lime storage tank	1 m^3	293	1.2	Carbon steel	3000	1990	3852
E-601	Filter bag house	12455 m^3/h	443	1.2	Carbon steel	23790	2002	23790
E-602	Fly ash container (3)	1 m^3	443	1.2	Carbon steel	3000	1990	3852
E-701	Ash quenching tank system	Packaged	873	1.2	Carbon steel	5000	1990	5000
E-702	Wastewater treatment system	22.00 m^3/day	293	1.2	–	73505	1990	94380
E-801	Packaging unit	Packaged	293	1.2	–	25707	1990	25707
E-802	Conveyor × 5 (100 ft)	2 tonnes/h	773	1.2	Carbon steel	22000	1990	141240
E-901	Stack	0.33 m × 50 m	443	1.2	Carbon steel	7722	1990	10000
Total equipment cost								1193273

tor of 15% for carrier delivery of those equipment items to the site; hence the total delivered equipment cost is US$ 1,372,264. The equipment list in Table 5 is for a process with a processing rate of 30 tonnes bamboo per day and around 6.6 tonnes activated carbon is produced. The range of process options considered in this project will be discussed in Section 4.3.6 later.

A “Lang” factor method is used to calculate the rest of the capital investment based on the total purchase equipment cost. This technique, proposed originally by Lang [18], is used quite frequently to an accuracy of ±20–30%. This approach recognizes that the cost of a process plant is obtained by multiplying the basic equipment cost by some factor to approximate the total capital investment. The rest of the capital investment is divided into direct costs and indirect costs of the project fixed capital cost.

4.3.1.2. Direct costs. For stand-alone plant. Besides the equipment cost, many other factors should be considered in the estimation of the capital investment such as installation, piping and site development in order to complete the process plant. The direct-cost items that are incurred in the construction of a plant, in addition to the cost of the equipment items are:

1. purchased-equipment erection, installation;
2. piping, including insulation and painting;
3. electrical equipment and materials, power and lighting;
4. instrumentation and controls;
5. process buildings and structures;
6. yard improvements (site development);
7. service facilities (utilities), provision of plant for steam, water, air, firefighting services;
8. land.

The direct-cost factor used in the estimation of the capital cost is given in Table 6 and the direct costs of different items are also shown. From the table, the total direct plant cost of the bamboo carbonization process is US$ 4,222,084. A continuous-emission-monitoring (CEM) unit is installed at “the end of the pipe” or stack to ensure the quality of the gas emission does not exceed the government set limits in the best practicable mean (BPM 12/1) guidelines for incinerator plant [20]. The cost of CEM including installation is US$ 240,385; hence, the revised total direct plant cost of the activated carbon production from the bamboo carbonization process is US$ 4,462,469.

For integrated plant. As these factors are changed by the removal of several equipment items, the modified form of

Table 6
Total direct plant cost for the bamboo carbonization stand-alone plant

Item	Typical factors for estimation of project direct fixed capital cost for different process types			Value of bamboo carbonization plant items for different process types (US$)		
	Fluids – solid	Solids	Fluids	Fluids – solid	Solids	Fluids
Equipment-delivered cost	100	100	100	426994	365418	579852
Equipment erection	39	45	47	166528	164438	272531
Instrumentation and controls	13	9	18	55509	32888	104373
Piping	31	16	66	132368	58467	382702
Electrical	10	10	11	42699	36542	63784
Building, process	29	25	18	123828	91355	104373
Yard improvements	10	13	10	42699	47504	57985
Service facilities	55	40	70	234847	146167	405897
Land	6	6	6	25620	21925	34791
Total	293	264	346	1251092	964704	2006289
Total direct plant cost				4222084		

Table 7
Total direct plant cost for the bamboo carbonization integrated plant

Item	Typical factors for estimation of project direct fixed capital cost for different process types			Value of bamboo carbonization plant items for different process types (US$)		
	Fluids – solid	Solids	Fluids	Fluids – solid	Solids	Fluids
Equipment-delivered cost	100	100	100	385896	344079	459815
Equipment erection	39	45	47	150499	154835	216113
Instrumentation and controls	13	9	18	50166	30967	82767
Piping	31	16	66	119628	55053	303478
Electrical	10	10	11	38590	34408	50580
Building, process	29	25	18	111910	86020	82767
Yard improvements	10	13	10	38590	44730	45981
Service facilities	55	40	70	212243	137632	321870
Land	6	6	6	23154	20645	27589
Total	293	264	346	1130674	908368	1590958
Total direct plant cost				3630000		

Table 6 is shown in Table 7. The total direct plant cost (including CEM installation) of the proposed activated carbon manufacturing integrated plant is US$ 3,870,385.

4.3.1.3. Indirect costs. For stand-alone plant. In addition to the direct cost of the purchase and installation of equipment, the capital cost of a project will include the indirect cost the process plant. The indirect-cost items [17] that are incurred in the construction of a plant are:

1. engineering and supervision;
2. construction expense;
3. contractor's fee;
4. contingency.

The 'Lang' factor for engineering and supervision, construction expense, contractor's fee and contingencies used in the estimation of the capital cost and the indirect cost of those items are shown in Table 8. From the table, the total direct

Table 8
Total indirect plant cost for the bamboo carbonization stand-alone plant

Item	Typical factors for estimation of projection direct fixed capital cost for different process type			Value of bamboo carbonization plant items for different process types (US$)		
	Fluids – solid	Solids	Fluids	Fluids – solid	Solids	Fluids
Engineering and supervision	32	33	33	136638	120588	191351
Construction expense	34	39	41	145178	142513	237739
Contractor's fee	18	17	21	76859	62121	121769
Contingency	36	34	42	153718	124242	243538
Total	120	123	137	512393	449464	794397
Total indirect plant cost				1756254		

Table 9
Total indirect plant cost for the bamboo carbonization integrated plant

Item	Typical factors for estimation of projection direct fixed capital cost for different process type			Value of bamboo carbonization plant items for different process types (US$)		
	Fluids – solid	Solids	Fluids	Fluids – solid	Solids	Fluids
Engineering and supervision	32	33	33	123487	113546	151739
Construction expense	34	39	41	131204	134191	188524
Contractor's fee	18	17	21	69461	58493	96561
Contingency	36	34	42	138922	116987	193122
Total	120	123	137	463075	423217	629946
Total indirect plant cost				1516238		

plant cost of the production of activated carbon process is US$ 1,756,254. Hence, the fixed capital investment of the production of activated carbon from the bamboo carbonization plant is US$ 6,218,723 which is equal to the sum of the direct plant cost and indirect plant cost.

For integrated plant. These factors are influenced by the equipment item capital costs and therefore Table 8 needs to be modified as shown in Table 9. Hence, the fixed capital investment of the activated carbon manufacturing integrated plant, which is equal to the sum of the direct and indirect plant cost, is US$ 5,386,622.

4.3.1.4. Working capital. The working capital for an industrial plant consists of the total amount of money invested in raw materials and supplies carried in stock, finished products in stock and semi-finished products in the process of being manufactured, accounts receivable, cash kept on hand for monthly payment of operating expenses, such as salaries, wages, and raw-material purchases, accounts payable and taxes payable. The ratio of working capital to total capital investment varies with different companies, but most chemical plants use an initial working capital amounting to 5–20% of the total capital investment. This percentage may increase to as much as 30% or more for companies producing products of seasonal demand because of the large inventories. The 'Lang' factor of working capital used in the estimation is shown in Table 10. In this project, the working capital is around 15% of the total capital investment in both stand-alone and integrated plants since the production of activated carbon is a simple process and the working capital of this bamboo carbonization stand-alone and integrated plants are US$ 1,063,133 and US$ 914,977, respectively (see Table 10).

Table 11
Summary of the total capital investment of the stand-alone plant activated carbon manufacturing

	Percent	US$
Delivered-equipment cost	20.6	1532521
Direct cost (including equipment cost)	60.1	4462469
Indirect cost	23.6	1756254
Working capital	14.3	1063133
EIA (1%) + HAZOP (1%)	2.0	148609
Total capital investment	100.0	7430465

4.3.1.5. Costs summary of total capital investment. For stand-alone plant. By adding the direct plant cost, indirect plant cost and working capital, the total investment required can be estimated. However, an Environmental Impact Assessment (EIA) and HAZOP safety study may be required in the production of activated carbon plant and the cost of the EIA and HAZOP study is assumed to be 2% of the total capital investment. The total capital investment for this project is US$ 7,430,465. The cost summary of the total capital investment of the activated carbon production process is shown in Table 11.

For integrated plant. These factors are influenced by the equipment item capital costs and therefore Table 11 needs to be modified as shown in Table 12. The total capital investment for the integrated bamboo carbonization plant will be US$ 6,430,203. About US$ 1 million can be saved on the total capacity investment by integrated the bamboo carbonization plant into other major processing facility.

4.3.2. Production costs

The determination of the necessary capital investment is only one part of a complete cost and evaluation estimate. An-

Table 10
Working capital for the bamboo carbonization process

Working Capital (about 15% of total capital investment)	Typical factors for estimation of projection working capital cost for different process type			Value of bamboo carbonization plant items for different process types (US$)		
	Fluids – solid	Solids	Fluids	Fluids – solid	Solids	Fluids
Stand-alone plant	74	68	86	315975	248484	498673
Work capital cost				1063133		
Integrated plant	74	68	86	285563	233974	395441
Work capital cost				914977		

Table 12
Summary of the total capital investment of the activated carbon manufacturing integrated plant

	Percent	US$
Delivered-equipment cost	21.0	1350045
Direct cost (including equipment cost)	60.2	3870385
Indirect cost	23.6	1516238
Working capital	14.2	914977
EIA (1%) + HAZOP (1%)	2.0	128604
Total capital investment	100.0	6430203

other equally important part is the estimation of the cost of operating the plant. The total production cost is generally divided into the categories of manufacturing costs and general expenses. All expenses directly connected with the manufacturing operation or the physical equipment of a process plant itself are included in the manufacturing costs. The manufacturing costs are divided into two main groups as follows: (1) fixed operating costs and (2) variable operating costs. The general expenses are involved in any company's operations. The total production costs are calculated on an annual basis in this project.

4.3.2.1. Fixed operating costs. For stand-alone plant. Fixed operating cost are expenses are which practically constant from year to year and do not vary widely with changes in production rate. These are the bills that have to be paid whatever the quantity of "product" produced. The items of the fixed operating costs are:

1. maintenance;
2. operating labor;
3. supervision and clerical;
4. plant overheads;
5. plant spares;
6. insurance.

The capital charges represent interest on a capital loan which is often recovered using a depreciation technique. We have not considered this but when considering the return on investment this fact should be considered. The fixed operating cost items and its factors using in this project are presented in Table 13, the total fixed operating cost is US$ 1,116,851.

For integrated plant. The fixed operating costs are based on seven components shown in Table 14. As item 1, maintenance, is a percentage of the fixed capital investment, therefore, the maintenance cost will be been changed. Operating labor will decrease slightly as the existing plants will have an operating team. Therefore, the number of workers per shift will reduce to 4 from 5. Due to the change in operating labor, supervision/clerical, laboratory and plant overheads will all decrease by 20%. Plant spares, insurance will also be changed due to the change of maintenance and fixed capital investment while royalties/patents will stay the same. The details of fixed operating cost items for integrated tyre plant are presented in Table 14, the total fixed operating cost is around US$ 0.86 million. About US$ 250,000 can be saved on the total fixed operating cost by integrated the bamboo carbonization plant into other major processing facility.

Table 13
Summary of the fixed operating cost items and its factors for stand-alone plant

Fixed operating costs items	Values used in the carbonization project	US$
Maintenance	5% of fixed capital	373123
Operating labor	5 shift workers, 3 shifts per day, HK$50/h	254499
Supervision and clerical	15% of operating labor	38175
Plant overheads	50% of total labor and maintenance	332898
Plant spares	15% of maintenance	55969
Insurance	1% of fixed capital investment	62187
Total fixed operating cost		1116851

Table 14
Summary of the fixed operating cost items and its factors for integrated plant

Fixed operating costs items	Values used in the carbonization project	US$
Maintenance	5% of fixed capital	323197
Operating labor	4 shift workers, 3 shifts per day, HK$50/h	203599
Supervision and clerical	15% of operating labor	24432
Plant overheads	50% of total labor and maintenance	220491
Plant spares	15% of maintenance	38784
Insurance	1% of fixed capital investment	53866
Total fixed operating cost		864369

4.3.2.2. Variable operating costs. For stand-alone plant. Variable operating costs include expenses directly associated with the manufacturing operation and they are dependent on the amount of product produced. The variable operating cost items are shown below:

1. raw materials;
2. utilities;
3. miscellaneous operating materials.

It is assumed that the raw material of bamboo is obtained from the construction and demolition (C&D) waste material, so the cost of this bamboo is zero in the evaluation. The plant will be operated for 330 days of the year with the rest of time for maintenance and 30 tonnes per day of bamboo will be carbonized in this activated carbon production plant. Table 15 shows the raw material required and the corresponding es-

Table 15
Estimated prices of raw materials for stand-alone and integrated plants

Raw material	Quantity (per annum)	Price US$/unit	US$
Bamboo	9900000	0.000	0
Lime	57756	0.11	6353
KOH	407647	1.16	943142
Total			949495

Table 16
Estimated costs of utilities in the activated carbon production process for stand-alone and integrated plants

Utility	Quantity (per annum)	Price US$/unit	US$
Electricity	200 kW	0	0
Water	12217 m^3	0.589/m^3	7346
Nitrogen	79200 kg	2.31	182952
Total			190298

timated prices for the activated carbon production process. The prices given are delivered prices.

The quantities of different utilities required per annum and the current costs of utilities for the activated carbon production process are shown in Table 16. We have assumed 5% of water (~1500 m^3 per year) in the close-loop boiler system will be lost during the electricity generation process (from blowdown and purging). The quantity of water usage for washing the activated carbon after the carbonization process is around 8700 m^3 per year and around 2100 m^3 water per year is required in the bamboo chemical activation process by the KOH solution. For chemical activation process, it is assumed 10% of KOH (~2470 kg/day) will be lost during the bamboo carbonization process.

The cost of liquid nitrogen is around US$ 2.06 per liter and the expansion ratio of liquid nitrogen to gaseous nitrogen is around 700, therefore, the cost of nitrogen gas is around US$ 2.31 per kg. The nitrogen gas acts as a purging gas to provide an oxygen-free environment in the carbonization furnace and will not be consumed within the carbonization reaction. Thus, once the carbonization furnace is filled with nitrogen, only a small amount of nitrogen is required to maintain an inert atmosphere. It is estimated that the usage rate of nitrogen is 8 m/h (or 10 kg/h) and this is used to purge the carbonization furnace during the process.

Another utility required in the activated carbon production is electricity in which the electricity is mainly used to drive all the motors, conveyors and pumps in the plant and the consumption is estimated at 200 kW. Therefore, no electricity cost is required to pay in this process since about 300 kW electricity is generated during the production of activated carbon from the bamboo carbonization process. The cost of miscellaneous materials (including packaging) is taken as 10% of the maintenance cost and the cost is US$ 37,312. The total variable operating costs are summarized in Table 17. The total manufacturing cost, the sum of fixed and variable operating cost, is US$ 2,293,957.

Table 17
Summary of the variable operating cost items for stand-alone and integrated plants

Variable operating costs items	US$
Raw materials	949495
Utilities	190298
Miscellaneous materials	37312
Total	1177106

Table 18
Summary of the general expense for stand-alone plant

General expense items	Factor	US$
Administrative expenses	15% of total labor and maintenance	99870
Sales expenses	11% of total manufacturing cost	252335
Research and development expense	8% of total manufacturing cost	183517
Total		535721

Table 19
Summary of the general expense for integrated plant

General expense items	Factor	US$
Administrative expenses	15% of total labor and maintenance	82684
Sales expenses	11% of total manufacturing cost	224013
Research and development expense	8% of total manufacturing cost	162919
Total		469616

For integrated plant. Based on the raw materials and utilities in Table 17, more will be need in the existing units of the existing plants. Therefore, no reduction in these variable production costs in proposed. Hence, the total manufacturing cost of the integrated plant is US$ 2,036,483.

4.3.2.3. General expenses. For stand-alone plant. Besides, the fixed and variable manufacturing costs, other general expenses are involved in any company's operations. These general expenses are administrative expenses, distribution and marketing expenses and research and development expenses. The general expenses of the Bamboo Carbonization Plant are US$ 535,721 as shown in Table 18.

For integrated plant. The general expenses items will change to a small extent as there are based on a percentage of labor costs and the manufacturing costs. These are shown in Table 19. The general expenses for integrated plant are US$ 469,616.

4.3.2.4. Costs summary of total production cost. For stand-alone plant. By adding the fixed operating cost, variable operating cost and general expenses, the total production cost required can be estimated. The cost summary of the total production cost of the stand-alone plant is shown in Table 20. The total annual production cost for this stand-alone activation carbon manufacturing process is US$ 2,829,678. A 39.5% of total production cost is due to the fixed operating

Table 20
Summary of the total production cost of the bamboo carbonization stand-alone plant

	Percent	Cost (US$)
Fixed operating cost	39.47	1116851
Variable operating cost	41.60	1177106
General expenses	18.93	535721
Total production cost	100.00	2829678

Table 21
Summary of the total production cost of the bamboo carbonization integrated plant

	Percent	Cost (US$)
Fixed operating cost	34.49	864369
Variable operating cost	46.77	1172113
General expenses	18.74	469616
Total production cost	100.00	2506099

costs and the variable operating cost is 41.6% of total production cost in which more than 80% variable operating cost is spent on the raw material of potassium hydroxide (KOH).

For integrated plant. Similarly, the cost summary of the total production cost for the integrated plant is listed in Table 21. The total annual production cost for this integrated activation carbon manufacturing process is 2.5 million dollars.

4.3.3. Revenues for the bamboo carbonization process

The revenues of the bamboo carbonization process options mainly come from the direct sales of activated carbons. Based on the usage of 30 tonnes of bamboo per day, the activated carbon production capacity is around 6.6 tonnes per day, and the product yield is 22.5%. The selling price of activated carbon largely depends on its quality, and the price could range from US$ 0.82 (from China) to 3.11 (from Japan) per kg. It is expected that this plant is able to produce moderate to high quality activated carbons. Based on the fact that the pricing pressure would be intense due to continuing competition from other suppliers particularly in China, the initial selling price of the activated carbon will be set at US$ 1.93 per kg. A sensitivity analysis has been performed to test the effect of the selling price on the overall economic evaluation, which will be discussed later in this paper. A breakdown of revenues from different sources is shown in Table 22. The annual sales revenues from the activated carbon manufacturing plant based on the capacity of 30 tonnes of bamboo per day will be US$ 4,183,172. The annual sales revenues for both stand-alone and integrated process plants are the same.

4.3.4. Simple estimate on return on investment (ROI)

Before performing the detailed economic evaluation, a simple return on investment ROI is calculated as a measure of annual rate of return on capital employed by the proposed activated carbon manufacturing project. In engineering economic evaluation, it is usually defined as the percent ratio of average yearly profit (net cash inflow) over the productive life of the project, divided by total initial investment. A positive ROI means the annual revenue is larger than the production cost; in other word, the plant is profitable.

Table 22
Summary of revenues generated from the sand-alone and integrated plants

	Quantity (per annum)	Unit price	Revenues (US$)
Activated carbon	2169672 kg	US$ 1.93 per kg	4183172
Total sales revenues			4183172

- *For stand-alone plant*.

$$\text{ROI} = \frac{\text{annual profit}}{\text{total capital investment}} \times 100\%$$
$$= \frac{\text{annual sales revenue} - \text{annual production cost}}{\text{total capital investment}}$$
$$\times 100\% = \frac{\text{US\$}\,4,183,172 - \text{US\$}2,829,678}{\text{US\$}\,7,430,465}$$
$$\times 100\% = 18.2\%$$

- *For integrated plant*.

$$\text{ROI} = \frac{\text{US\$}\,4,183,172 - \text{US\$}\,2,506,099}{\text{US\$}\,6,430,203} \times 100\%$$
$$= 26.1\%$$

4.3.5. Economic evaluation of projects

The prime purpose of the project evaluation is to permit a decision to be taken on whether or not to proceed with a new plant or plant modification. If the result shows that a better rate of return on the investment than could be achieved by leaving it in the bank with an additional factor for risk, then it is probable that the project will proceed. On the contrast, if a lower return is obtained, the project is unlikely to be implemented. In this study the project period of the bamboo carbonization plant is set to be 16 years and the carbon production will be started after the first 2-year construction period. The cumulative cash flow diagrams of the stand-alone and integrated plants are presented in Fig. 6 (0% discount rate), Figs. 7 and 8 (at different discount rates). It is noted that the payback period of the stand-alone plant is 8 years after the plant starts operation at the discount rate of 0% from the start of the project. Alternatively it is 6 years after the start of production. The project net profit value (NPV) of the stand-alone plant project at the discount rate of 0% is around

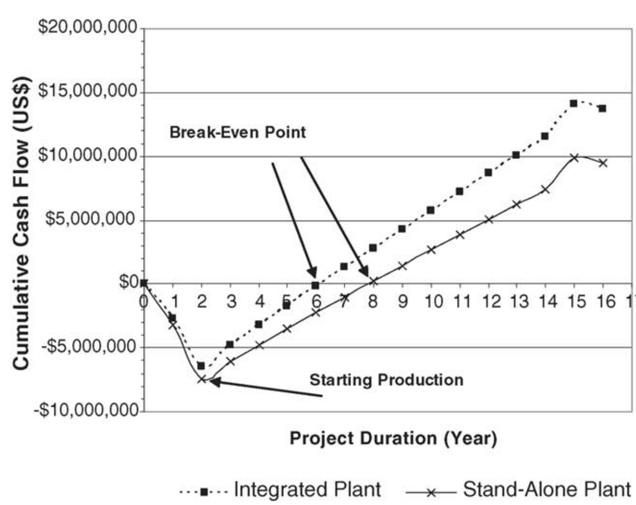

Fig. 6. Cumulative Cash flow for stand-alone and integrated activated carbon plants at 0% discount factors.

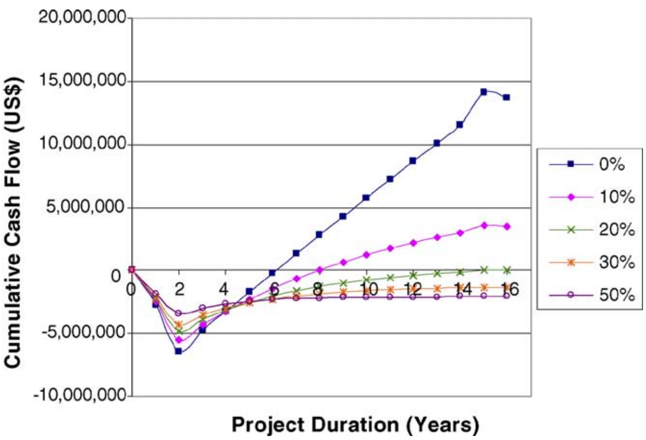

Fig. 7. Cumulative cash flow for stand-alone plant at different discount factors.

US$ 9,470,000. For the integrated process plant, the payback time at the discount rate of 0% is 6 years and it is 4 years after the start of production. The NPV of the integrated plant is 44.5% more than the NPV of stand-alone plant and it is around US$ 13,700,000.

Fig. 9 shows the relationship between the NPV for this project and the applied discount rate, internal rate of return (IRR) diagram. It provides a measure of the rate of return expected on a project investment over the whole project life, and so the larger the value of the IRR the more economically attractive is the project. From the graph, the IRR is where the curve cuts the discount rate axis at NPV is equal to zero and it is found to be 13.0 and 20.1% for the stand-alone plant and integrated plant, respectively.

Table 23 is a summary of the major indicators of the performance on the economic matter of the stand-alone and integrated process projects and it was found that integrated process shows more profitable than stand-alone process. The positive values of both ROI and IRR together of both stand-alone and integrated processes with a 6 and 8 years long, respectively, payback period reveal a profitable prospect of the proposed production process. In the following sections a

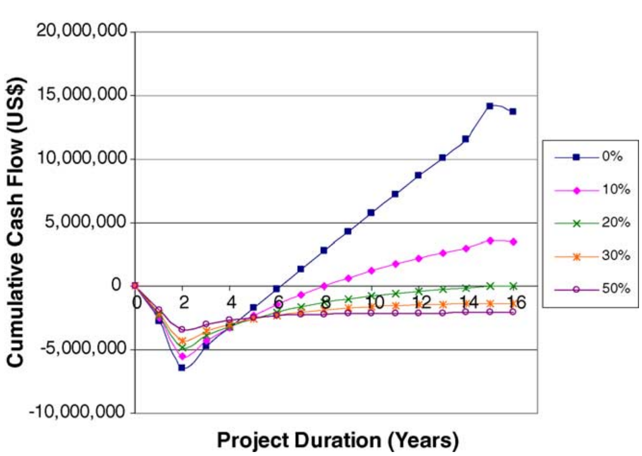

Fig. 8. Cumulative cash flow for integrated plant at different discount factors.

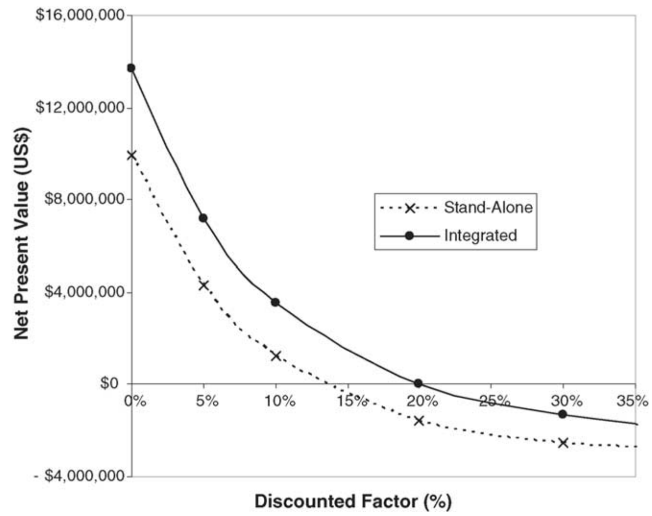

Fig. 9. Internal rate of return (IRR) of the stand-alone and integrated activated carbon plants.

sensitivity analysis has been carried out on the stand-alone process only.

4.3.6. Sensitivity analysis

In order to investigate the effect on the economic viability of a project of possible changes in the forecast data which contribute to the project cash flows, a sensitivity analysis for the manufacture of activated carbon from bamboo carbonization process is undertaken. This involves selecting the five main factors affecting the economic attractiveness of the project which are taken into consideration. These factors are listed below:

- total capital investment;
- cost of KOH;
- operating labor wage;
- selling price of activated carbon;
- production capacity.

Table 24 shows the effect of variations of these five forecast factors over the range −25 to +25%, with 5% increment each time, to see the effects on the project net present value. The rows for zero variation are the base NPV values corresponding to the original forecasts and economic evaluation. The data in Table 24 is shown graphically in Fig. 10. The steeper the slope of the line for a factor, the more sensi-

Table 23
Major indicators on stand-alone and integrated processes project economic performance

	Stand-alone process	Integrated process
Return on investment (ROI) (%)	18.2	26.1
Internal rate of return (IRR) (%)	13.0	20.1
Payback period (at 0% discount rate) (years)	8	6
Net profit value (NPV) (US$)	9470000	13700000

Table 24
Sensitivity of NPV (million US$-based value NPV = 9.47) to various factors

% Variation	Cost of KOH	Operating labor wage	Total capital investment	Activated carbon selling price	Production capacity
−25	12.51	11.00	13.09	−1.89	3.25
−20	11.90	10.70	12.37	0.38	4.55
−15	11.29	10.39	11.64	2.65	5.77
−10	10.68	10.08	10.92	4.93	6.99
−5	10.08	9.77	10.19	7.20	8.23
0	9.47	9.47	9.47	9.47	9.47
5	8.86	9.16	8.74	11.74	10.68
10	8.25	8.85	8.02	14.01	11.94
15	7.64	8.54	7.29	16.28	13.19
20	7.03	8.24	6.57	18.55	14.43
25	6.42	7.93	5.84	20.82	15.68

tive is the NPV to that factor. From the diagram, comparing the slopes of five lines obtained by difference factors, 25% changes in operating labor wage shows little effect on NPV while the NPV is more sensitive to the change of the cost of KOH and the total capital investment and is much more sensitive to the production capacity of the plant and the selling price of activated carbon. When the production capacity and the selling price of the activated carbon increase, the corresponding NPV will increase significantly. The opposite trend can however be observed for the total capital investment, the operating labor wage, the cost of KOH.

4.3.6.1. Selling price of activated carbon. For instance, a 10% increase of activated carbon selling price from HK$ 15 per kg to HK$ 16.5 per kg would induce a 48% increase in the NPV. Thus the selling price of the activated carbon is the most important of the key issues which dictates the viability of the project; however the selling price is associated with many other parameters such as the quality of the activated carbon produced, the demand of the activated carbon and the competition of the other activated carbon sources, which may make the selling prices fluctuate with the external factors. Fig. 11 shows the NPV and ROI of this project at different price of the activated carbon. Detailed experimental studies must be performed in the future, in order to find out the optimum conditions, such as temperature, activation methods and agents, etc., for the bamboo carbonization process to produce a high BET surface area and high adsorption ability (high quality) activated carbon from bamboo cane. A high quality activated carbon is required which can be most effectively removed dioxin and heavy metals from the effluent of the MSW incineration process.

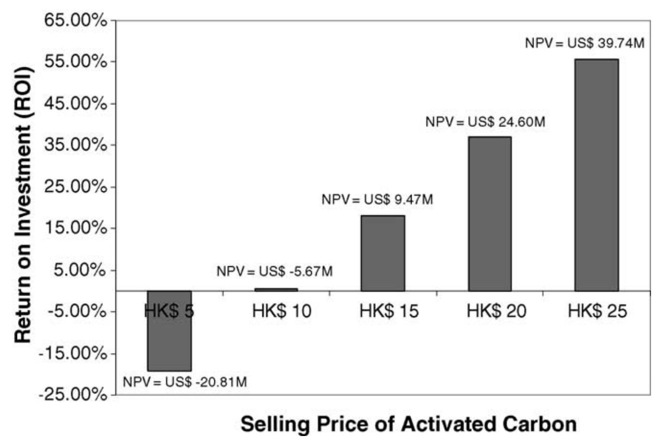

Fig. 11. Comparison of ROI and NPV for different selling price of activated carbon.

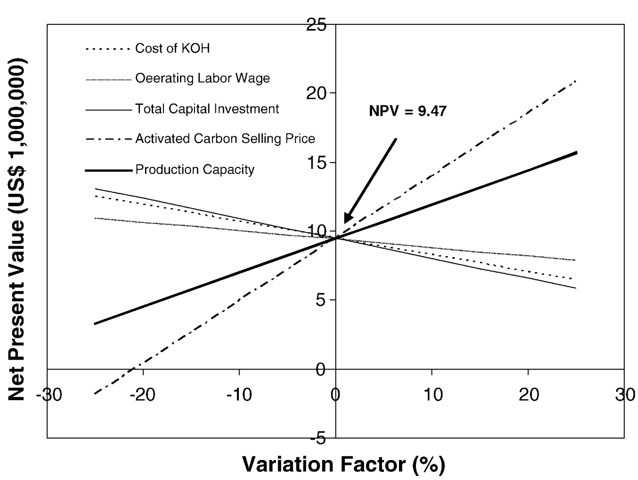

Fig. 10. NPV sensitivity analysis of the bamboo carbonization process.

4.3.6.2. Production capacity. From Fig. 10, it is found that the production capacity of the bamboo carbonization process is the second most significant factor affecting the NPV of this project. The change in the production capacity will also make a change in the total capital investment because the size and cost of the equipment items change accordingly. A "six-tenths-factor rule" [18] has been used to calculate the cost of the equipment items at different production capacities:

$$\text{new equipment cost} = \text{old equipment cost} \times \left(\frac{\text{new production capacity}}{\text{production capacity}}\right)^{0.6}$$

The NPV and ROI at different bamboo carbonization capacities at different selling prices of activated carbon are shown in Table 25 and some data in the table are presented

Table 25
Return on investment (ROI) and net present value (NPV) for bamboo carbonization plant at various conditions

Selling price of activated carbon	Daily bamboo processing capacity (tonnes)			
	15	30	45	60
Return on investment (ROI) for bamboo carbonization plant (%)				
HK$ 10	−12.5	−0.55	5.76	10.1
HK$ 15	0.95	18.2	27.9	34.7
HK$ 20	14.4	37.0	50.1	59.3
Net present value (NPV million US$) for bamboo carbonization plant				
HK$ 10	−10.7	−5.67	−0.73	4.46
HK$ 15	−3.13	9.47	21.9	34.7
HK$ 20	4.44	24.6	44.7	65.0

graphically in Fig. 12. The result of the ROI for the bamboo plant at different plant capacities is a function of selling prices of activated carbon. When the selling price of the activated carbon is HK$ 15, the ROI of this project with 15–60 tonnes/day bamboo carbonization capacity increases from 14.36 to 34.70% and the NPV of this project with 15, 30, 45, 60 tonnes/day bamboo capacity is US$ 4.44, 9.47, 22.0 and 65.0 million, respectively. It is a fact that the larger the production capacity of the activated carbon, the higher the rate of return of the project. With a larger bamboo carbonization capacity, 60 tonnes/day, we can reduce the selling price of activated carbon from $15.0 to $11.7 with the same value of the ROI to increase the competitiveness of the product.

The bamboo carbonization capacity of plant depends on the potential market demand of the activated carbon and the amount of dumped bamboo scaffolding waste discarded in a country each year. For example, in Hong Kong, the annual amount of activated carbon imported into Hong Kong in the past 10 years is around 2000–3000 tonnes (6.0–8.8 tonnes/day, 330 operating days). If the yield of bamboo carbonization is approximately equal to 22.5% according to the experimental results, then the amount of waste bamboo required is 27–40 tonnes/day. Therefore, it is suggest that the proposed maximum capacity of the bamboo carbonization plant will be 40 tonnes/day. From the waste statistics report, over 50,000 tonnes (∼136 tonnes/day) of bamboo scaffolding waste each year is dumped as construction waste in Hong Kong, around 30% of daily waste bamboo will be treated in the 40 tonnes bamboo carbonization plant to produce 8.8 tonnes high-quality activated carbon per day selling at around HK$ 15 per kg. The ROI, payback time and, NPV of the bamboo plant will be 25.1%, 4.3 years and US$ 17.8 million, respectively.

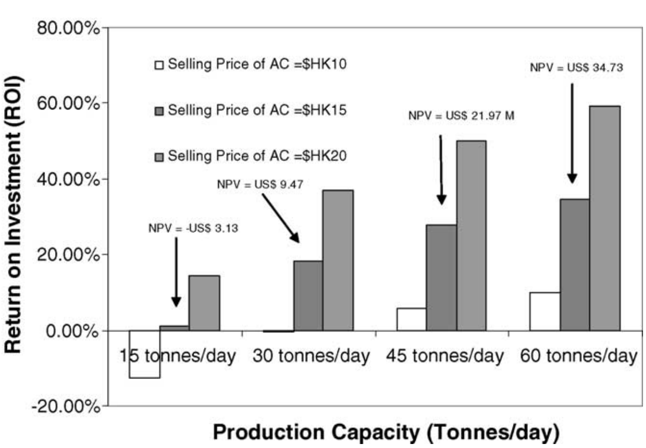

Fig. 12. Comparison of ROI for different production capacity as a function of activated carbon selling price.

4.3.6.3. Equipment from China-based company. Another significant factor affecting the viability of the project is the total capital investment. A “Lang” factor method is used to calculate the rest of the total capital investment based on the total purchase equipment cost. The total capital investment is calculated by multiplying the total purchased equipment by an appropriate factor which accounts for all direct and indirect capital cost. Therefore, the cost of the equipment items is a main factor to control the NPV in the sensitivity analysis of the total capital investment. The equipment cost data presented in Table 5 are US-based equipment costs, but the equipment cost from China could be half or even one-third of the US prices. The price of the equipment items bought and constructed from “Chinese” contract companies are much cheaper than the American companies and the potential cost savings of the equipment items can save more than 50%. If the equipment cost of the plant could be purchased from China at a half price as compared with those bought from US, the equipment cost would be decreased from US$ 1.37 to 0.69 million, and the resulting ROI will soar from 18.2 to 46.6%, with the assumption that the activated carbon would be of the same quality and sold at the same price. The production of activated carbon from bamboo carbonization process will become a very attractive investment since the payback period of the plant is less than 3 years. If the equipment cost from China Company is only one-third compared to that of a US Company, the rate of investment (ROI) of the bamboo carbonization plant will increase from 18.2 to 73.3%. The cumulative cash flow profiles for these three cases are presented in Fig. 13. Moreover, for the case of half price equipment cost from China Company, the activated carbon selling price can also be reduced from US$ 1.93 per kg to US$ 1.54 per kg to increase the competitiveness of the product, the ROI will

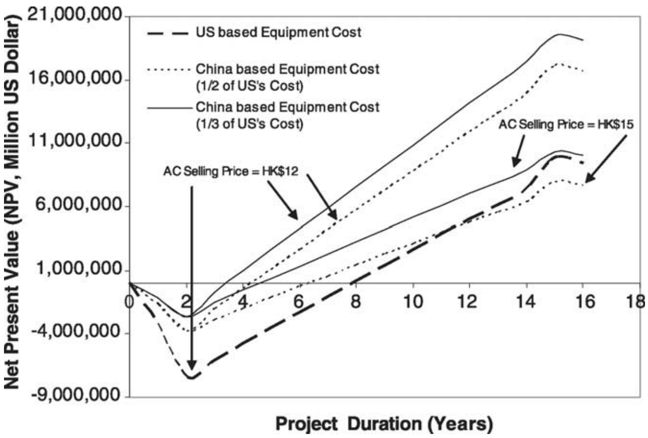

Fig. 13. Comparison between US- and China-based equipment costs on the effect of cumulative cash flow for the bamboo carbonization plant.

become 24.8% and payback period will reduce to around 4.2 from 6 years. The cumulative cash flow profiles for difference prices of activated carbon with two China-based equipment costs (half of the US prices and one-third of the US prices) are also presented in Fig. 13. A summary of NPV, ROI, IRR and payback period of the bamboo carbonization plant based on US-contract and China-contract equipments at different selling price of activated carbon are shown in Table 26.

4.3.6.4. Chemical activation agent. The activation process is to enhance the volume and to enlarge the diameters of the pores which were created during the carbonization process and to create some new porosity. The two common activation processes are chemical activation and physical activation process. Since chemical activation usually is carried out when the raw material is of wood origin, therefore, it is designed to use chemical activation method in the bamboo carbonization process. From Fig. 10, it is found that the change for the cost of potassium hydroxide (KOH) has a significant effect as well as the total capital investment on the NPV of this project. Potassium hydroxide is one of the common chemical agents using in the production of high quality activated carbon and the other widely used activating agents are potassium carbonate, phosphoric acid and sulfuric acid. Using different chemical activation agents in the bamboo carbonization process should provide different quality activated carbon and the yields of the production are also different. In order to compare the sensitivity of different chemical activation agents on the NPV of this project, if the consumption of the chemical activated agents in the process are the same, then it is assumed that the quality and production rate of the activated carbon from the bamboo carbonization process is almost the same (activated carbon sold at the same price). The quotation prices of four different chemical activation agents are shown in Table 27. The resulting ROI and NPV of this project using these four chemical activation agents are also tabulated in Table 27. Using sulfuric acid, the lowest price chemical agent, instead of potassium hydroxide in the carbonization process will increase NPV from US$ 9.47 to 16.2 million and increase ROI from 18.2 to 26.6%, increasing 71% profit of this project. Fig. 14 shows the relationship between the chemical activation agents and the ROI of this project. Using a cheap chemical activation agent with high activation

Table 27
Sensitivity analysis on chemical activation agent

Chemical activation agent	Price	ROI (%)	NPV (million US$)
Potassium hydroxide (KOH)	HK$ 9	18.2	9.47
Potassium carbonate (K_2CO_3)	HK$ 8	19.9	10.8
Phosphoric acid (H_3PO_4)	HK$ 6	23.2	13.5
Sulfuric acid (H_2SO_4)	HK$ 4	26.6	16.2

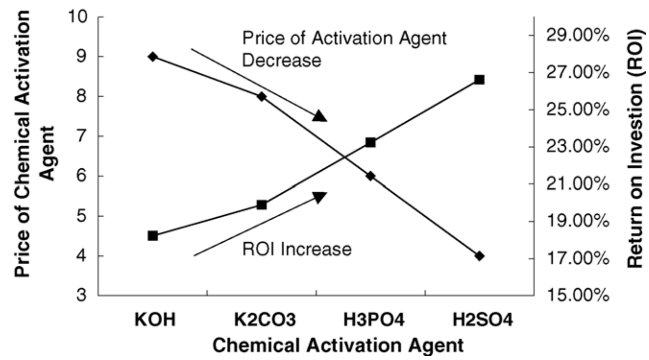

Fig. 14. Relationship between chemical activation agents and ROI of this project.

Table 26
Return on investment (ROI) and net present value (NPV) of bamboo carbonization plant at various equipment contractors

	US-based equipment cost	China-based equipment cost (1/2 of US's cost)	China-based equipment cost (1/3 of US's cost)
Selling price of activated carbon = US$ 1.93 (HK$ 15)			
NPV (million US$)	9.47	16.7	19.1
ROI (%)	18.2	46.6	73.3
IRR (%)	13.0	35.9	53.8
Payback period (years)	8	4.2	3.4
Selling price of activated carbon = US$ 1.54 (HK$ 12)			
NPV (million US$)	0.38	7.63	10.5
ROI (%)	7.0	24.8	41.6
IRR (%)	0.6	19.0	32.3
Payback period (years)	14.5	6.3	4.7

power on the bamboo carbonization process is important and significant to provide a high return on investment. However, to perform a more detailed and accurate economic evaluation on the effect of chemical activation agents, laboratory studies on the production quality of activated carbon with different chemical activation agents including yield of the bamboo carbonization, adsorption ability of activated carbon and amount of chemical activation agent consumption must be carried out in future.

4.3.6.5. Electricity generation system. Other consideration for the plant design of the sensitivity analysis is electricity generation system. In the bamboo carbonization plant, a steam turbine is designed to recover the heat energy from the hot flue gas to generate electricity (∼300 kW) for the production plant and the neighboring cement production plant, thus saving on the electricity cost. The cost of the steam turbine is around US$ 200,000 and contributes to 17% of the total equipment cost. In order to investigate the economic effectiveness of installing the electricity generation system, a process simulation for the bamboo carbonization process without generating electricity, no steam turbine, is carried out. The rate of investment (ROI) of the bamboo carbonization plant will increase from 18.2% (NPV = US$ 9.47 million) to 22.2% (NPV = US$ 10.1 million) since the bamboo carbonization plant can generate around 300 kW but the electricity demand of the plant is assumed to be 200 kW. If we can utilize all the rest of electricity to the neighboring cement production plant, the ROI of the bamboo carbonization plant with electricity generation system will become 19.4% (NPV = US$ 10.4 million). For the above results, the installation of the electricity generation system in the bamboo carbonization plant does not provide a good economical return and reduce the ROI of the production plant. Moreover, a cheaper gas cooler system can be used to replace the boiler package system if electricity generation is not considered; it can further reduce the total capacity investment and increase the ROI of the bamboo carbonization plant.

5. Conclusion

A feasibility study for the carbonization of bamboo scaffolding waste to make activated carbon has been performed in this paper based on 30 tonnes of bamboo waste per day throughput. This paper consists of a preliminary process design based on various literature sources and an economic evaluation, in which the estimation of the capital investment, the production cost, the return on investment (ROI), the cash flow and the internal rate of return (IRR), has been carried out. For the stand-alone activated carbon plant, it is found that ROI is up to 18.2% when the total capital investment is HK$ 7,430,000. The internal rate of return is 13.0%, showing a profitable prospect of the production plant. The payback period is estimated to be 6 years after the commencement of production. For the integrated activated carbon plant, the total capital investment of the bamboo treatment process can be reduced to HK$ 6,430,000 plant, therefore the ROI increases to 26.1% and the internal rate of return becomes 20.1%. The payback period is estimated to 4 years after the commencement of production.

Sensitivity analysis reveals that the cash flow of the project would be increased or decreased up to 40, 65 and 120% by varying production factors of cost of KOH, production capacity and selling price of activated carbon, respectively, in the extent of ±25%. There are some limiting assumptions in the costing calculation:

1. Accuracy may vary in the range of ±25–30%, as equipment costs and detailed equipment designs at this stage have not been finalized.
2. The costs of major equipments are based on the price in United States. It could be lower if suppliers from other countries (for instance, mainland China) could offer cheaper equipment items.
3. Energy integration analysis of the entire process has not yet been conducted. The costs relating to energy consumption have not been fully analyzed at this stage of design.
4. Other weaknesses relate to the actual values of the Lang factorial method, e.g. cost of land. Absolute values of Lang factors have been used in the financial calculations, whereas these parameters are a range of numbers. Each component needs to be assessed carefully for greater accuracy.
5. The quality of the activated carbon has a major effect on its market value. More laboratory tests are required to assess the range and quality of tyre-based activated carbon.

Acknowledgements

The authors are grateful to ITF and RGC, Hong Kong SAR, for the provision of financial support during this research programme.

References

[1] Market, Report No. 11A001, Market survey on activated carbon industry in China, Guangzhou CCM Chemicals Co. Ltd, China, July 2001.
[2] F.Y.S. So, F.K.W. Wong, Bamboo scaffolding development in Hong Kong—a critical review, in: Proceedings of the Symposium on Bamboo and Metal Scaffolding, Harbour Plaza Hotel, Hong Kong, 1998.
[3] J.J.A. Jansen, Bamboo in building structures, Ph.D. Thesis, Edindhoven University of Technology, Holland, 1981.
[4] C.K. Lee, Bamboo Scaffolding in Hong Kong, Part 1, Department of Civil and Structural Engineering, Hong Kong Polytechnic University, 1995.
[5] C.C. Chang, T.X. Yu, An Engineering Study for Improving Safety and Reliability of Bamboo Scaffoldings, Hong Kong Occupational Safety and Health Council, 2002.

[6] Hong Kong Environmental Protection Department, Environment Hong Kong in 1993, 1993.
[7] T. Asada, S. Ishihara, T. Yamane, A. Toba, A. Yamada, K. Oikawa, Science of bamboo charcoal: study on carbonizing temperature of bamboo charcoal and removal capability of harmful gases, J. Health Sci. 48 (6) (2002) 473–479.
[8] K. Ohe, Y. Nagae, S. Nakamura, Y. Baba, Removal of nitrate anion by carbonaceous materials prepared from bamboo and coconut shell, J. Chem. Eng. Jpn. 36 (4) (2003) 511–515.
[9] F.C. Wu, R.L. Tseng, R.S. Juang, Preparation of activated carbons from bamboo and their adsorption abilities for dyes and phenol, J. Environ. Sci. Health A 34 (9) (1999) 1753–1775.
[10] J.J. Pis, M. Mahamud, J.A. Pajares, J.B. Parra, R.C. Bansal, Preparation of active carbons from coal. Part III. Activation of char, Fuel Process. Technol. 57 (3) (1998) 149–161.
[11] K. Kadirvelu, C. Namasivayam, Activated carbon from coconut coirpith as metal adsorbent: adsorption of Cd(II) from aqueous solution, Adv. Environ. Res. 7 (2) (2002) 471–478.
[12] G. Skodras, T. Orfanoudaki, E. Kakaras, G.P. Sakellaropoulos, Production of special activated carbon from lignite for environmental purposes, Fuel Process. Technol. 77 (1998) 75–87.
[13] M. Valix, W.H. Cheung, G. McKay, Preparation of activated carbon using low temperature carbonisation and physical activation of high ash raw bagasse for acid dye adsorption, Chemosphere 56 (5) (2004) 493–501.
[14] M. Teker, M. Imamoglu, O. Saltabas, Adsorption of copper and cadmium ions by activated carbon from rice hulls, Turkish J. Chem. 2 (1999) 185–191.
[15] D.S. Kim, Activated carbon from peach stones using phosphoric acid activation at medium temperatures, J. Environ. Sci. Health, Part A 39 (5) (2004) 1301–1318.
[16] G.D. Ulrich, A Guide to Chemical Engineering Process Design and Economics, Wiley, New York, 1984.
[17] R.K. Sinnott, Coulson and Richardson's Chemical Engineering, 3rd ed., vol. 6, Butterworths/Heinemann, Oxford, 1998.
[18] M.S. Peter, K.D. Timmerhaus, Plant Design and Economics for Chemical Engineers, 5th ed., McGraw-Hill, New York, 2003.
[19] Chemical and Engineering News: "News Edition" of the American Chemical Society, vol. 82, 2004.
[20] Hong Kong Environmental Protection Department, A guidance Note on The Best Practicable Means for Incinerators (MSW Incineration), BPM 12/1, 2001.