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Original Article

Comparative life cycle assessment of biomass-based and coal-based activated carbon production

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Abstract

Activated carbon is an effective adsorbent due to its high porosity, large surface area and high surface reactivity. Activated carbon is commonly produced from coal, which is a non-renewable resource. Alternative source such as biomass-based activated carbon is being explored nowadays. However, the environmental impact of biomass-based activated carbon produced is still not clearly quantified. Thus, in this study, the impact of production of biomass-based activated carbon was compared with the base case of production of coal-based activated carbon. The environmental impact of both biomass and coal-based activated carbon in terms of global warming potential (GWP), acidification potential (AP) and eutrophication potential (EP) was evaluated based on life cycle assessment (LCA) framework outlined in ISO 14040. A cradle to gate analysis of the biomass-based activated carbon production, starting from the harvesting of the biomass to the production of activated carbon are compared with the coal-based activated carbon production, from the mining of coal to the production of activated carbon. The input and output data of the biomass-based and coal activated carbon were obtained from the literature. The results show that biomass-based activated carbon has milder impact to the environment in terms of GWP, EP and AP compared to coal-based activated carbon. The outcome of this study provides a better understanding on the environmental impact of production of biomass-based activated carbon.

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1 Introduction

Activated carbon (AC) is a common adsorbent to remove various pollutant in both air and water pollution [1,2]. It is effective due to its high porosity, large surface area, variable characteristics of surface chemistry, and high degree of surface reactivity [3]. Almost all carbon-containing material can be converted into activated carbon. This includes biomass waste [4]. Application of activated carbon in the adsorption process was found to be successful in elimination of a wide range of pollutant and carcinogenic compounds from the water, such as organic and non-organic pollutants, dye and pharmaceuticals discharge. [5].

The demand for activated carbon is high and the global market for activated carbon was US$2.1 billion in year 2014 [6]. Due to the expansion of activated carbon application, this figure is expected to increase annually [7]. Activated carbon is commonly manufactured from coal, which is a non-renewable resource [8]. Recently, there are efforts to replace coal-based activated carbon with renewable resources

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such as biomass waste [9,10]. The biomass waste can be recovered through agricultural activities within a cycle of cultivation period and it can be considered as renewable resources. Hence, biomass could be an alternative source to produce a greener and lower cost activated carbon [11].

Biochar is the primary source that can be produced from the thermochemical conversion of biomass by pyrolysis or gasification to produce activated carbon from biomass [12]. Pyrolysis is a thermal decomposition of raw materials in a furnace in an inert atmosphere under nitrogen gas purge. This process removes non-carbon species, such as nitrogen, oxygen, and hydrogen and increase the solid carbon content in order to produce biochar [13]. Meanwhile, gasification is an incomplete combustion process of carbon rich biomass that produces biochar, bio-oil and syngas.

There are two methods to activate biochar or biomass adsorbent into activated carbon, i.e., through physical activation or chemical activation. Activation of biomass adsorbent would result in the formation of highly porous surface to further enhance its performance as adsorbents [14]. Physical activation usually involves carbon dioxide and steam as activating agent to produce activated carbon. Meanwhile, chemical activation usually applies alkaline chemical agent, such as sodium hydroxide and potassium hydroxide as activating agent to convert biochar into activated carbon [15]. While each of the methods to produce the biochar and its eventual conversion into activated carbon has its own technical pros and cons, the potential environmental impact of different combination of methods to produce activated carbon from biomass and its comparison with activated carbon produced from coal is still not clearly quantified thus far.

Life cycle assessment (LCA) is a method for quantitatively compiling and evaluating the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle based on 14040 ISO standard. The standards are organized LCA into 4 different phases, which are (1) goal and scope definition, (2) inventory analysis, (3) life cycle impact assessment and (4) life cycle interpretation [16]. Loya-Gonzalez [17] conducted a LCA study to evaluate the environmental impacts of biomass-based activated carbon production by different impregnation ratio (impregnate in potassium hydroxide, KOH). They found that activated carbon produced from the highest impregnation ratio contributed most toward fossil depletion, climate change and human toxicity, because the production of every 1 kg of KOH required 73.2 g of coal brown, 633 g of coal hard, 282 L of natural gas, 87.9 g of crude oil and will released 2.3kg CO_2.

Gu et al. [18] evaluated the environmental impact of biochar-based activated carbon comparing with the coal-based activated carbon. The scope of the study started from forest residue extraction as the raw material of the biochar-based activated carbon, while, the process for coal-based activated carbon production started from the mining of coal . The study focused on steam activation (physical activation) for conversion of biochar into activated carbon. The study showed that biochar-based activated carbon consumed 35% lesser cumulative energy demand than the coal-based activated carbon during production process. The GWP of biochar-activated carbon was less than half of the GWP for coal-based activated carbon due to lower energy consumption (8.60 kg CO_2-eq per kg of biochar-based activated carbon produced compared to 18.28 kg CO_2-eq per kg of coal-based activated carbon produced).

On the other hand, Hjaila et al. [19] conducted a gate-to-gate LCA of activated carbon from olive-waste cake via pyrolysis process. High electricity consumption in the process lead to contribution of large amount of global warming gases (11.096 kg CO_2-eq/kg AC).

Activated carbon produced from biomass showed comparative efficiency as the coal-based activated carbon [20]. However, the environmental impact of the different production route or method (combination of pyrolysis or gasification with chemical activation or physical activation) could be different from one another and it should be quantified accordingly. Therefore, in this study, comparative LCA of production of biomass-based activated carbon and coal-based activated carbon, from cradle to gate, are carried out to evaluate its impact to the environment.

2 Methodology

2.1 Goal and Scope Definition

The functional unit for this study is 1 kg of activated carbon. The goal of this study is to compare the environmental impact of the production of biomass-based activated carbon with coal activated carbon from mining of the coal or harvesting of the biomass raw material (cradle) to the production of the activated carbon (gate). This study also aims to investigate the environmental impact associated with production of biomass based activated carbon via different reaction routes. This includes a combination of different activation method (chemical activation or physical activation), with thermochemical conversion method (gasification or pyrolysis). In order to compare the environmental impacts of coal activated carbon with biomass-based activated carbon, the data, obtained from literature sources were scaled to the functional unit of 1 kg basis of coal- and biomass-based activated carbon produced.

Fig. 1 and Fig. 2 illustrate the system boundaries of biomass-based activated carbon and coal-based activated carbon production process from cradle to gate. The absorption efficiency of activated carbon produced from all different five routes were comparable and it was supported with the BET surface area and porosity as well [21]. The input and output data included each process in the system boundary which releases environmental pollutants, such as the emission of carbon dioxide (CO_2), methane (CH_4), nitrogen oxides (NO_x) and sulphur dioxide (SO_2) into the atmosphere. Based on Fig. 1, raw materials (oil palm biomass), electricity and fuel are fed into the system. Meanwhile, for the quantification of pollutants, CO_2, CH_4, NO_X and SO_2 were considered as the emission into the air. SO_2 is also considered as wastewater emission when it is dissolved in water.

For biomass-based activated carbon production, oil palm biomass is selected as raw material. This is because it is an abundant and less expensive biomass in Malaysia [22,23]. The evaluation starts from harvesting of oil palm, extraction of biomass, chipping of biomass and pretreatment of biomass. For activation and conversion process, it is divided into 4 routes, which are pyrolysis with physical activation (Route 1), chemical activation with pyrolysis (Route 2), gasification with physical activation (Route 3) and chemical activation with gasification (Route 4). The byproduct of thermochemical conversion from the process such as bio-oil and biogas are not within the scope of this study. For gasification, bio-oil and biogas can be removed completely from the gasifier. For pyrolysis, biochar can be separated from byproduct biooil and biogas as downstream product for activation process.

Route 5 is the production process flow of conventional coal activated carbon (Fig. 2). The evaluation of production process of coal activated carbon starts from mining of bituminous coal, also known as black coal. After mining, the coal goes through cleaning and crushing [24]. The crushed coal is sent for activation after the pyrolysis process [25].

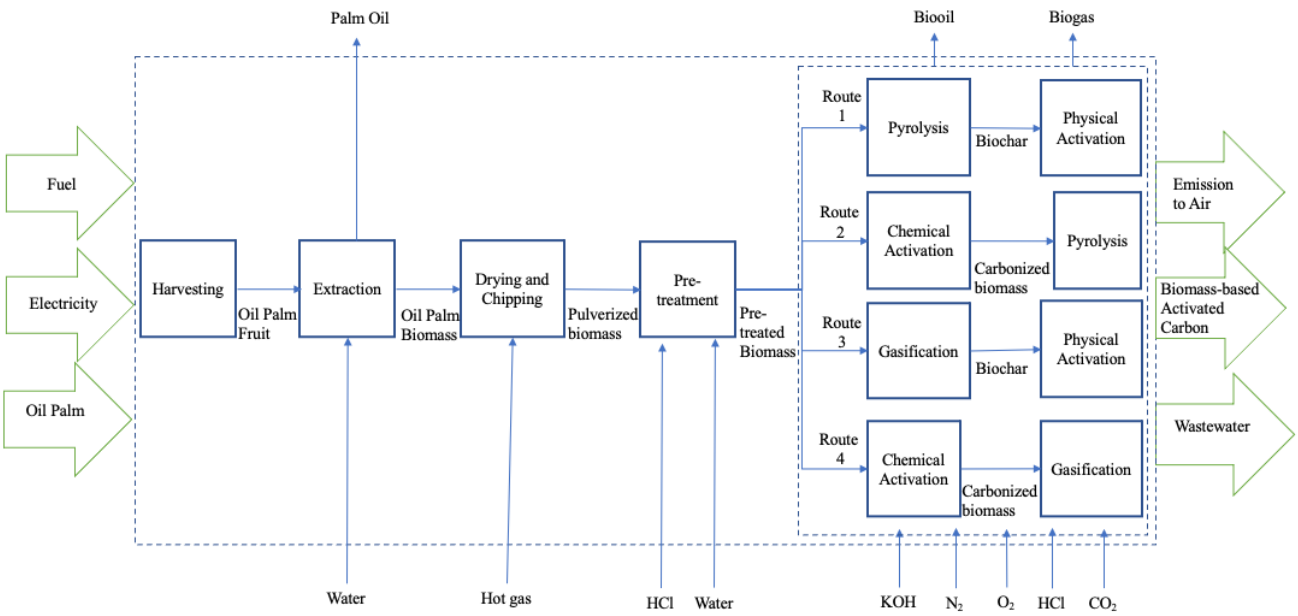

Fig. 1 System boundary of biomass-based activated carbon production process from cradle to gate (Route 1 – Route 4).

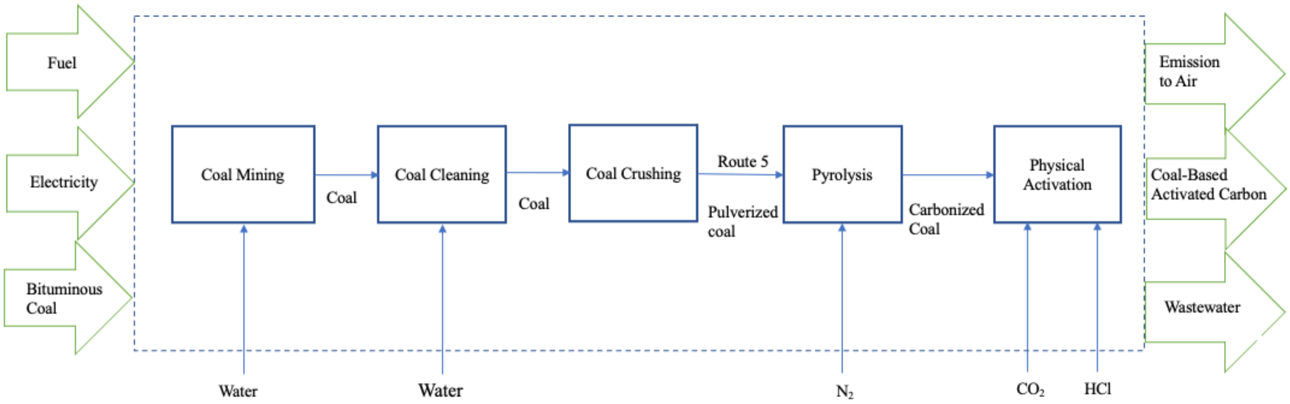

Fig. 2 System boundary of coal-based activated carbon production process from cradle to gate (Route 5).

2.2 Inventory Analysis

The input and output data for this study was collected from literature sources [19,26-35] for the life cycle inventory. The inventory was scaled to the functional unit of this study. The followings are the limitation and assumptions of data used in this study:

- Transportation is not included in this study as it is case-specific [36].
- Electricity is generated by coal-fired plant because coal is main fuel source in Malaysia [37]
- The setting for pyrolysis is consistent (nitrogen atmosphere, 2 hours and 450ºC) [38].
- The setting for gasification is consistent (oxygen atmosphere, 2 hours and 700 ºC) [39].
- The chemical activation utilizes potassium hydroxide (KOH) and impregnate with biomass for 30 minutes in 80 ºC [40,41].
- The physical activation utilizes carbon dioxide and the operating condition is 900 ºC for 3 hours in furnace [20].
- The technology process design and operational conditions is assumed to be in industrial scale.
- The plantation of oil palm is not considered in the scope of this study.
- Surface mining was considered because bituminous coal can be mined on the surface coal field, and it is less energy intensive (Route 5) [42].
- Gravity method was used to clean coal because this is the simplest and economic way to separate impurities from coal [24].

The power consumption and emission of pollutants (mass of pollutant, m_i) from each of the unit processes of the biomass-based and coal-based activated carbon production collected in the inventory was used to further calculate the selected environmental impact categories.

2.3 Impact Assessment

The main objective of the impact assessment is to translates the physical flows and interventions of the product system into relevant environmental indicator. The impact indicators selected in this study is Global Warming Potential (GWP), Acidification Potential (AP) and Eutrophication Potential (EP). This is because the production process would release significant amount of greenhouse gases (CO_2, CO, CH_4), acidic gases (SO_2) and nitrogen-based anion (NO_X) which could contribute towards the selected environmental impact [29,43].

The identified t pollutants were categorized and characterized into the selected impact indicators through the conversion factor listed in Table 1. The impact assessment was calculated using the formulae in Table 2 based on the quantities of the pollutant multiplying with the specific weighting factor in Table 1. The main parameters used in the formula are the mass (m_i) in kilogram (kg) of the particular pollutant released to environment multiplied with the pollutant's specific conversion indicator (GWP_i, AP_i and AP_i). It represents the environmental effect potential per mass unit of the specific considered pollutant.

Table 1 Pollutant and conversion factor for GWP, AP and EP [44].

Pollutant, *i*	**GWP**	**AP**	**EP**
	kg CO_2-eq/kg	kg SO_2-eq/kg	kg PO_4^{3-}-eq/kg
CH_4	21	0	0
CO_2	1	0	0
NO_X	0	0.7	0.13
SO_2	0	1	0

Table 2 Impact Assessment Indicator formulae and unit [44].

Indicator	**Formulae**	**Unit**
Global Warming Potential	$GWP = \sum_i GWP_i \times m_i$	kg CO_2-eq
Acidification Potential	$AP = \sum_i AP_i \times m_i$	kg SO_2-eq
Eutrophication Potential	$EP = \sum_i EP_i \times m_i$	kg PO_4^{3-}-eq

The conversion factors for electricity into pollutants is tabulated in Table 3. The different pollutants emission during the electricity generation was already considered in the conversion factors. The electricity used in this study was converted into the emission of pollutant (kg per kWh) as shown in Table 3. Coal-based electricity produces higher emission of CO_2 whereby diesel oil-based electricity produces higher emission of SO_2. In this study, it is assumed that the electricity generation is from coal because it is the main fuel sources in Malaysia [37]. Electricity generation from diesel oil is only considered for special cases such as harvesting of biomass. The harvesting machinery uses diesel oil to operate [26].

Table 3 Electricity to pollutants conversion factors [45,46].

Type of energy	**Emission (kg/kWh)**			
	CO_2	CO	NO_X	SO_2
Coal	1.18	0.0002	0.0052	0.0139
Diesel Oil	0.85	0.0002	0.0025	0.0164

3. Result and Discussion

3.1 Overall Results for Biomass-Based Activated Carbon

Fig. 3 shows the GWP, AP and EP of biomass-based activated carbon production for 4 different routes with detailed breakdown based on each process in the route. Generally, the environmental impact of GWP, AP and EP for biomass-based activated carbon production were mainly contributed by the electricity power consumption. Fuel such as coal and diesel oil were used to generate electricity, which lead to release of pollutants that contributed to GWP, EP and AP. Electricity consumption was noticeably high for physical activation and pyrolysis process because physical activation required high temperature of 900 °C and pyrolysis is an endothermic reaction. Thus, substantial heat is required to be supplied to maintain the high temperature of the process [47].

Harvesting process to chipping process of Route 3 and Route 4 shows higher GWP, AP and EP than Route 1 and Route 2. This is because, higher amount of biomass is needed to produce 1 kg of activated carbon due to lower yield from gasification process (Route 3 and Route 4) compared to pyrolysis process (Route 1 and Route 2) [48-50]. According to Pradana et al. [32], the gasification yield for biochar is 25.3% while the yield from pyrolysis process is 35% [51]. The same trend of GWP, AP and EP is also observed for pretreatment process of biomass due to the higher amount biomass required for the process. Route 2 applied chemical activation and a subsequent pyrolysis process while Route 4 applied chemical activation and a subsequent gasification process to produce activated carbon. Thus, for the chemical activation process, Route 4 utilizes more energy compared to Route 2 due to higher amount of raw material to be processed in Route 4.

For physical activation, the biomass goes through the thermochemical conversion first (pyrolysis for Route 1 or gasification for Route 3) before the activation process. Therefore, the same amount of raw material is fed into the physical activation process and similar amounts of pollutants is emitted from the physical activation process [29,32,33]. Hence, as shown in Fig. 3, similar level of GWP, AP and EP is observed.

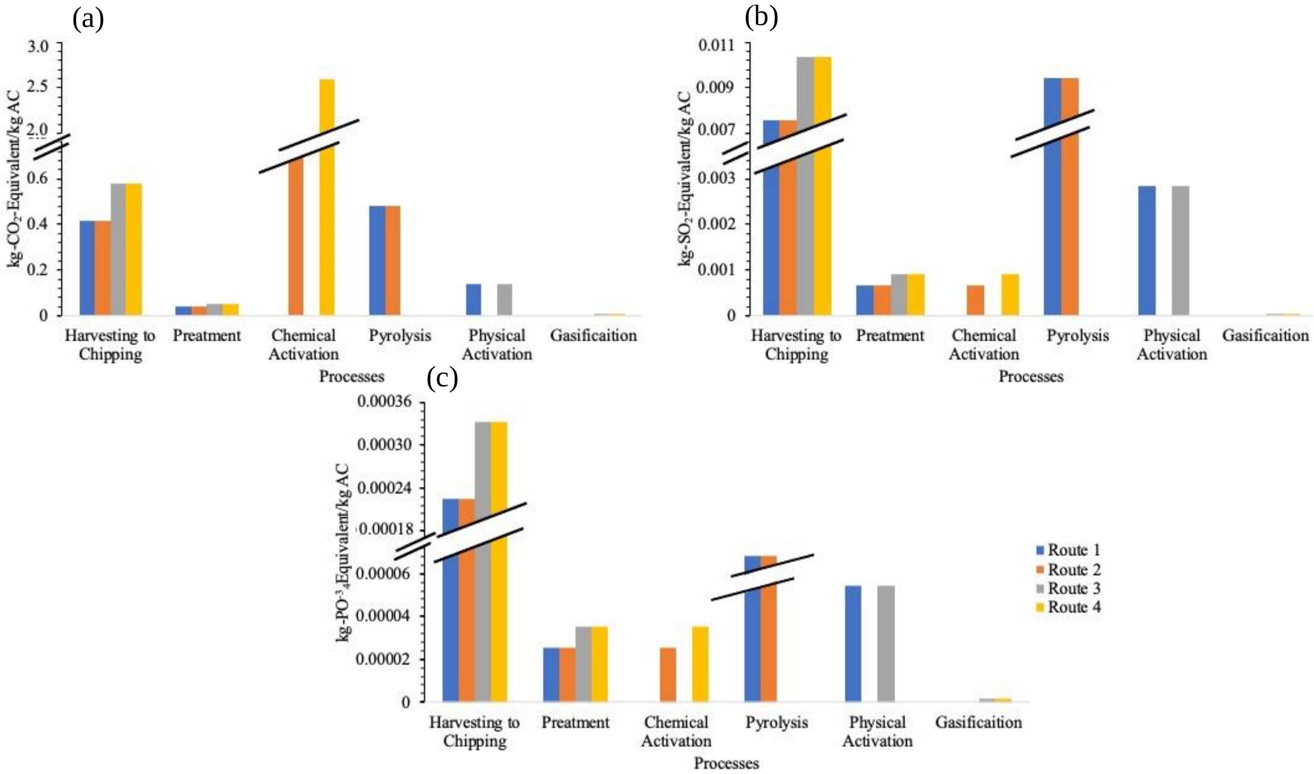

Fig. 3 Relative contribution made by different processes toward (a) GWP, (b) AP and (c) EP for Route 1 to Route 4.

Fig. 4 shows the total GWP, AP and EP of biomass-based activated carbon for each process route for biomass-based activated carbon production (Route 1 to Route 4). The harvesting to chipping process contributes to the GWP, AP and EP considerably due to electricity consumption for oil palm biomass extraction step and biomass chipping step. There are few processes in biomass extraction step, which are sterilization of fruit followed by stripping of fruitlet from the bunch. Fuel is needed in boiler to generate electricity by steam turbine to support those processes [52,53]. For biomass chipping process, hot gas generated by combustion of the fuel is used to dry up the high moisture oil palm biomass followed by chipping process [54]. For GWP, based on Fig. 4(a), it can be observed that Route 2 and Route 4 have similarly high contribution to followed by Route 1 and Route 3. Route 2 and Route 4 consist of chemical activation process. In the process, the chemical activation agent, KOH, reacts with the active intermediates at the carbon surface, releasing CO_2. Eqs. (1) to (4) show the reactions between the active intermediate with the carbon surface which leads to the release of CO, CO_2, and H_2 during chemical activation by KOH [31].

$$6KOH + 2C \rightarrow 2K + 2K_2CO_3 + 3H_2 \quad (1)$$

$$3K_2O + 2C + 3H_2O \rightarrow 2K + 3H_2 + 2K_2CO_3 \quad (2)$$

$$2K_2CO_3 + 4C \rightarrow 4K + 6CO \quad (3)$$

$$2K_2CO_3 + C \rightarrow 4K + 3CO_2 \quad (4)$$

Therefore, the high GWP for Route 2 and Route 4 was contributed from the chemical activation process. Gasification consumed lesser energy than pyrolysis due to controlled amount of oxygen supplied to gasifier to promote combustion [55]. Therefore, the total GWP for Route 1 is higher than Route 3.

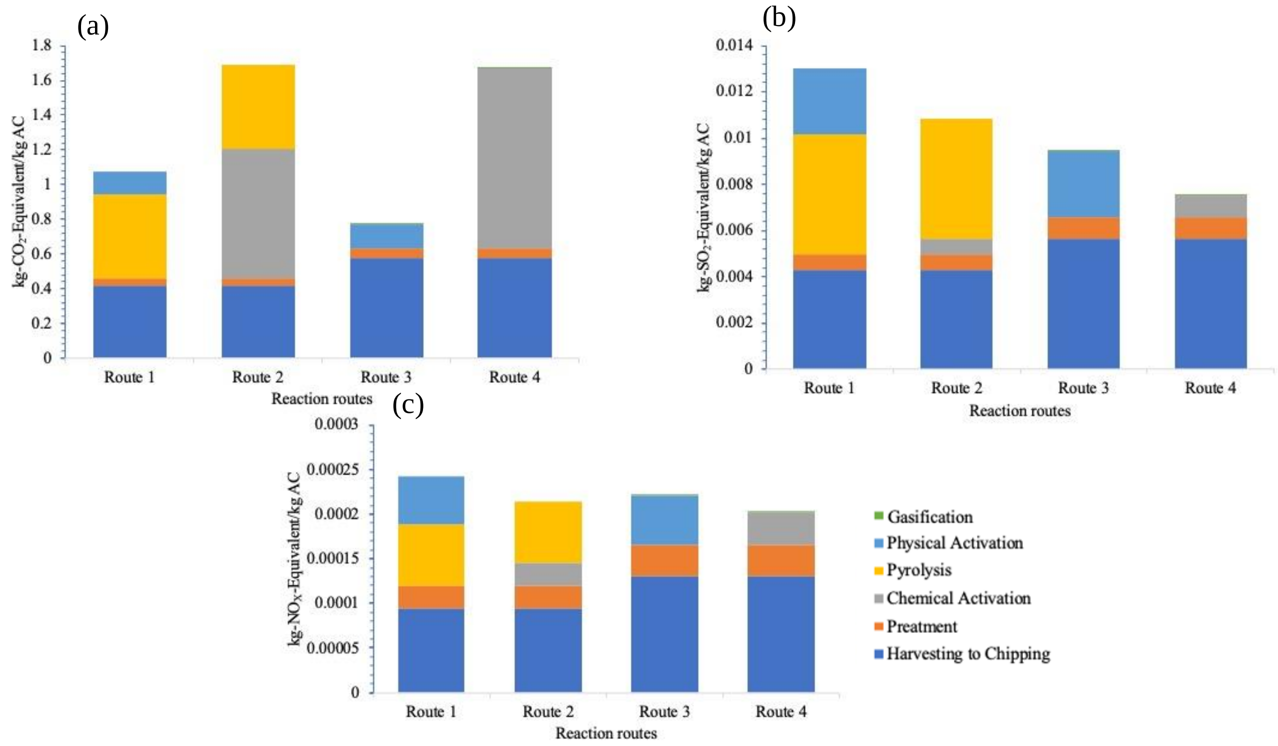

Fig. 4 Total (a) GWP, (b) AP and (c) EP of biomass-based activated carbon (Route 1 to Route 4)

From Fig. 4 (b) and (c), it can be observed that Route 1 has the highest AP and EP among the four routes to produce biomass-based activated carbon. The compounding effect from pyrolysis and physical activation which required substantial heat to maintain the high temperature of the processes contributed to the high AP and EP from Route 1 [47]. From Fig. 3 and Fig. 4, a very low contribution towards AP and EP from gasification process could be observed for Route 3 and Route 4 because gasification consumes a much lesser amount of energy than pyrolysis. This was due to the controlled amount of oxygen supplied to gasifier to promote combustion [55]. Overall, Route 4 shows the lowest AP and EP as chemical activation required lesser energy consumption with lower reaction temperature of 80 ^{o}C. It is worth noting that if a different chemical activating agent, such as phosphoric acid, is used for chemical activation, it could contribute to high EP level if the residual acid is water-washed and treated as emission from the process [19].

The summary result of GWP, AP and EP for biomass-based activated carbon for the 4 different routes is tabulated in Table 4. Among the 4 routes, the production of biomass-based activated carbon via gasification with physical activation (Route 3) contributed to the lowest GWP, although for AP and EP, its contribution level was comparable to Route 4. As such, Route 3 is expected to pose a lower environment impact when selected for the production of biomass-based activated carbon.

3.2 Comparison of Biomass-based Activated Carbon with Coal-based Activated Carbon

The analysis of environment impact of coal-based activated carbon are divided into two parts, where first part is coal mining process, coal crushing process and coal cleaning process. The second part is pyrolysis and physical activation of coal, which is the common route for production of activated carbon from coal [56]. Fig. 6 shows impact of Route 5 towards GWP, AP and EP. In general consumption of large amount of electricity in the second part of the process led to high GWP, AP and EP. High electricity consumption was required in furnace and activation chamber due to high reaction temperature requirement in the process [29]. There was huge amount of volatile gas on the coal surface such as CO_2 and SO_2 gases emitted during the activation process, which contributed to high GWP, AP and EP value [57]. In addition, volatile gas at surface of coal such as CH_4 would be released due to high temperature [58]. The impact of CH_4 is 21 times higher than CO_2 in terms of GWP.

Table 4 Summary result of GWP, AP and EP for biomass-based activated carbon.

Routes	Global Warming Potential (kg CO_2-eq/kg AC)	Acidification Potential (kg SO_2-eq/kg AC)	Eutrophication Potential (kg PO_4^{3-}-eq/kg AC)
Route 1	1.08	2.06×10^{-2}	4.87×10^{-4}
Route 2	2.81	1.86×10^{-2}	4.58×10^{-4}
Route 3	7.71×10^{-1}	1.45×10^{-2}	4.19×10^{-4}
Route 4	3.22	1.26×10^{-2}	4.00×10^{-4}

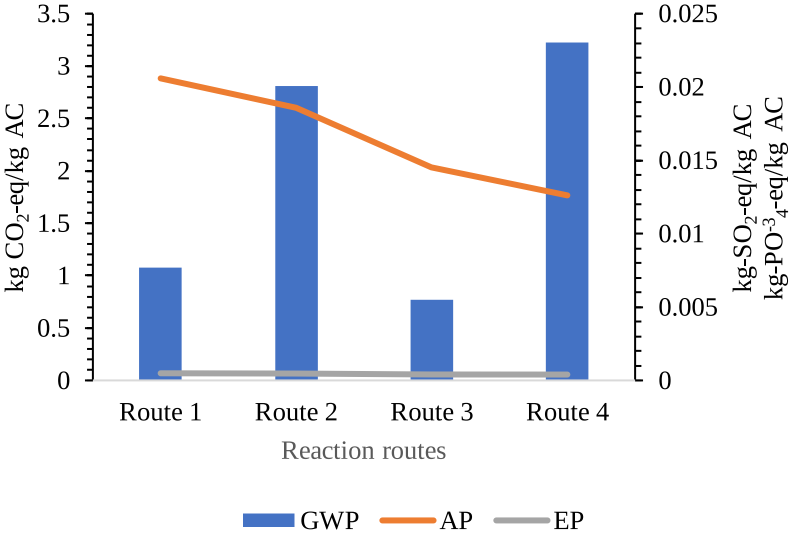

Fig. 5 Overall grand total pollutant emitted by biomass-based activated carbon.

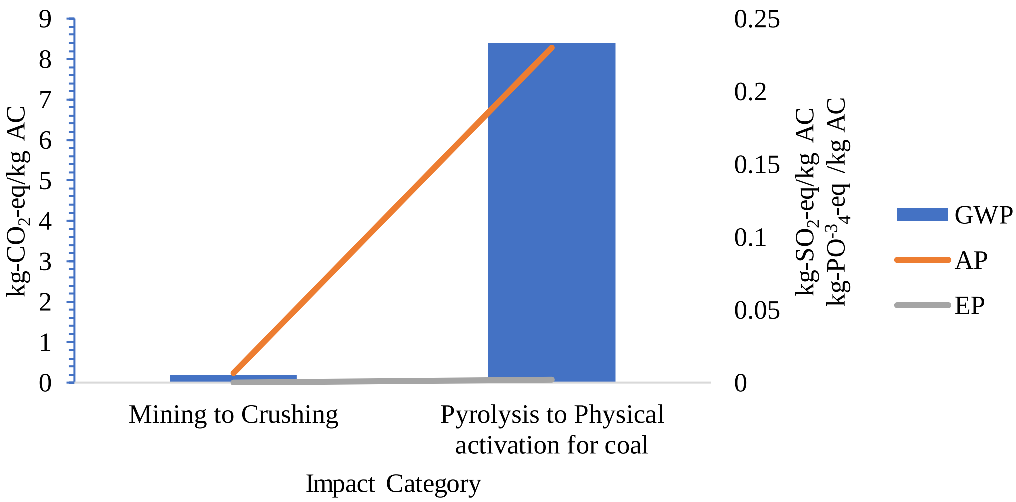

Fig. 6 Overall grand total pollutant emitted by coal-based activated carbon for different process (Route 5).

Figs. 7 to 9 shows an overall GWP, AP and EP of coal-based activated carbon (Route 5) in comparison with biomass-based activated carbon (Route 1 to Route 4). Route 5 shows the highest GWP, AP and EP value compared to the four routes for biomass-based activated carbon. As explained in the previous paragraph, the high electricity consumption and release of CH_4 from coal contributed to the high GWP.

As for the significantly higher AP and EP for Route 5 compared to the four routes for biomass-based activated carbon, the trend was also related to the high electricity consumption. The production of electricity itself, also released SO_2 and NO_X, contributing to AP and EP respectively [59]. In addition, the difference between coal-based activated carbon and biomass-based activated carbon is larger for AP than EP. This was due to the release of SO_2 during the coal mining process which further contributed to higher AP [60]. EP has a smaller difference between coal-based activated carbon and biomass-based activated carbon because there was release of NO_X at the plant harvesting process which consumed diesel oil for harvesting machinery [26].

Fig. 10 shows the overall environmental impacts of biomass-based activated carbon and coal-based activated carbon in terms of GWP, AP and EP. Route 5 posed the highest environmental impact, followed by Route 4, Route 2, Route 1 and Route 3. Coal-based activated carbon (Route 5) emitted approximately 8.6kg CO_2-eq/kg AC, 0.237kg SO_2-eq/kg and 0.002 PO_4^{3-}-eq/kg AC which is the highest among five routes. Therefore, in overall, production of activated carbon using biomass is expected to have milder impact towards the environment in terms of GWP, AP and EP. In addition, usage of biomass waste as raw material for activated carbon would contribute towards circular economy, give value the waste from plantation industry and reduce our dependency on non-renewable resources, i.e., coal.

According to study conducted by Abdullah et al. [61], large portion of plantation biomass are being treated with open burning or open dumping, which would cause severe environmental pollution as well as harboring pests and disease. Proper disposal of the biomass in large quality is difficult and expensive to the industries. Therefore, using biomass to produce activated carbon is highly beneficial in the point of decrease the cost of waste disposal and could be beneficial towards environmental protection.

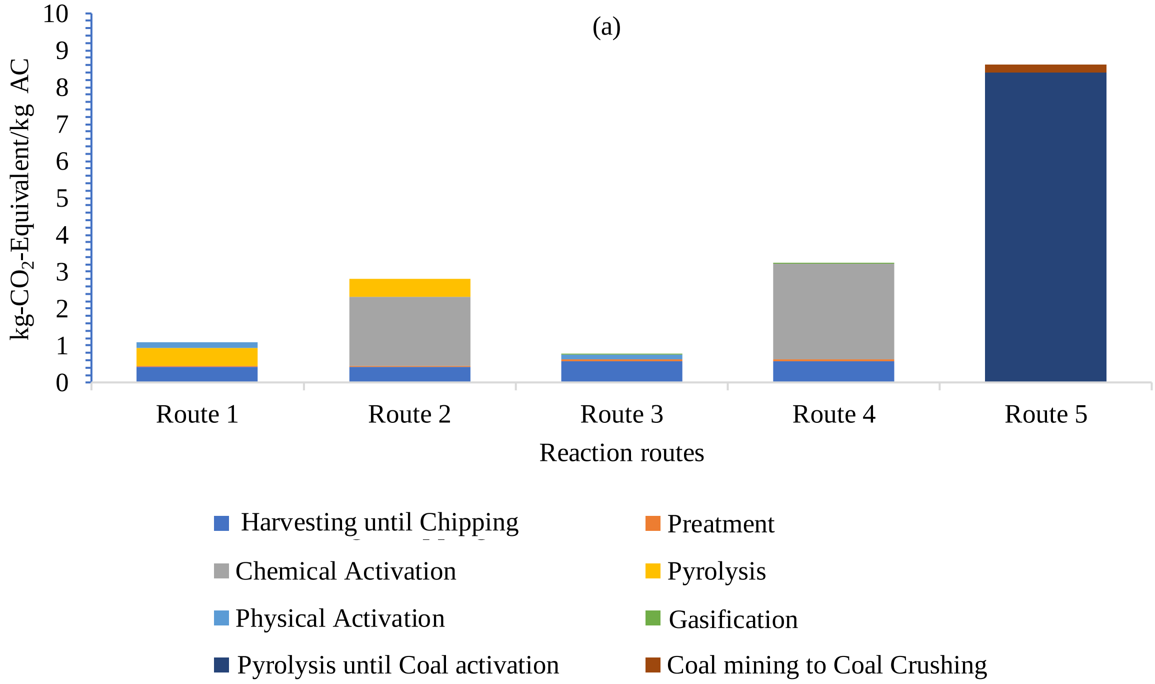

Fig. 7 GWP of coal-based activated carbon and biomass-based activated carbon.

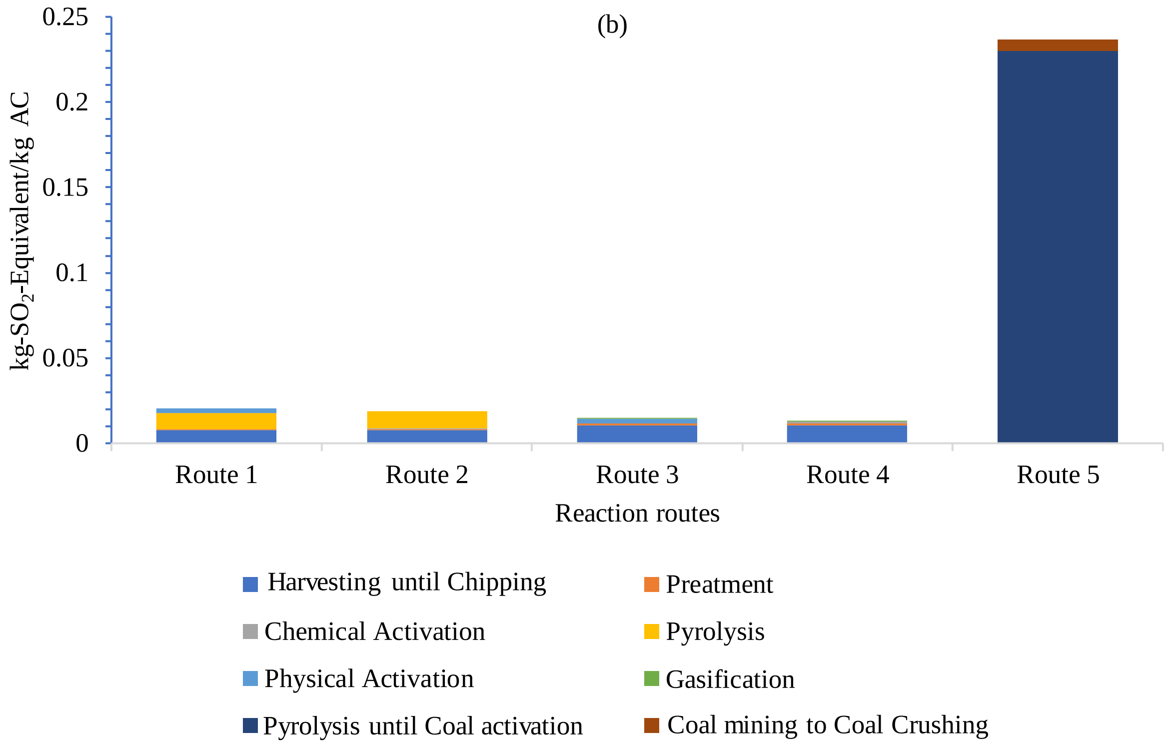

Fig. 8 EP of coal-based activated carbon and biomass-based activated carbon.

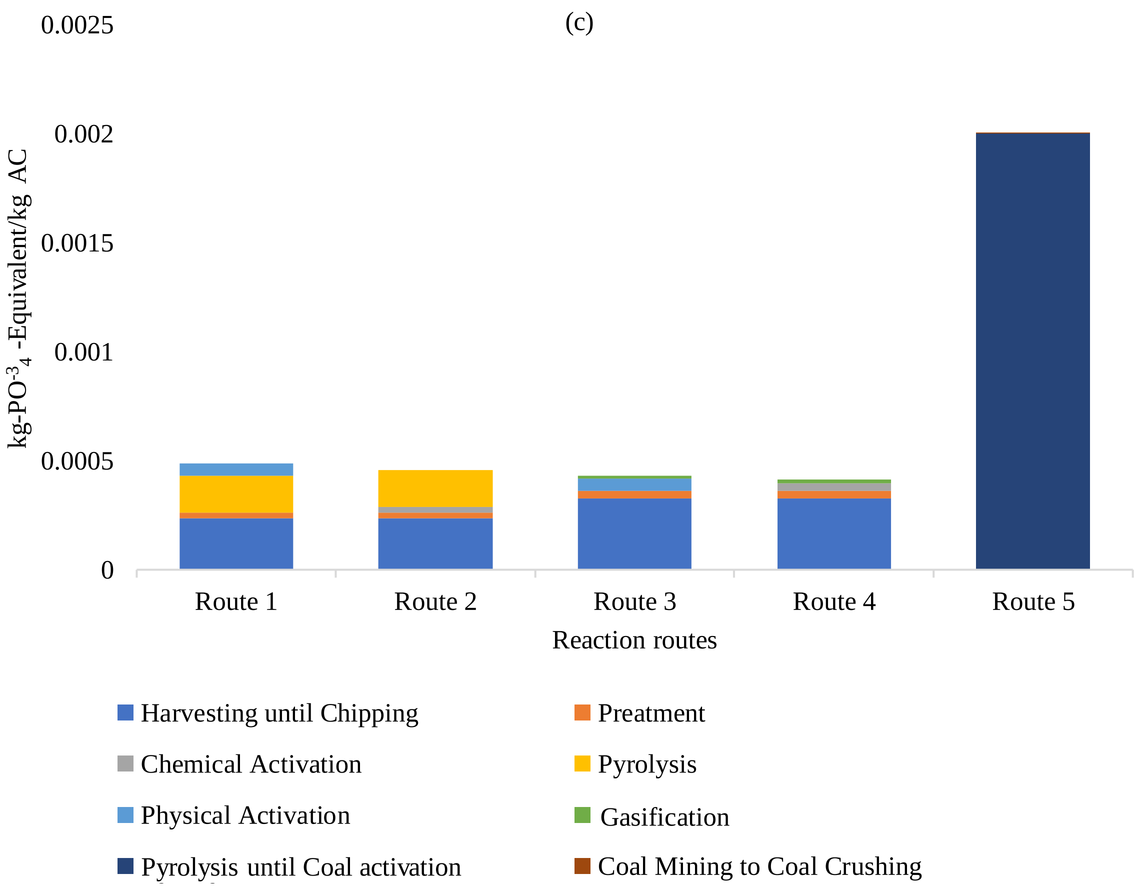

Fig. 9 EP of coal-based activated carbon and biomass-based activated carbon.

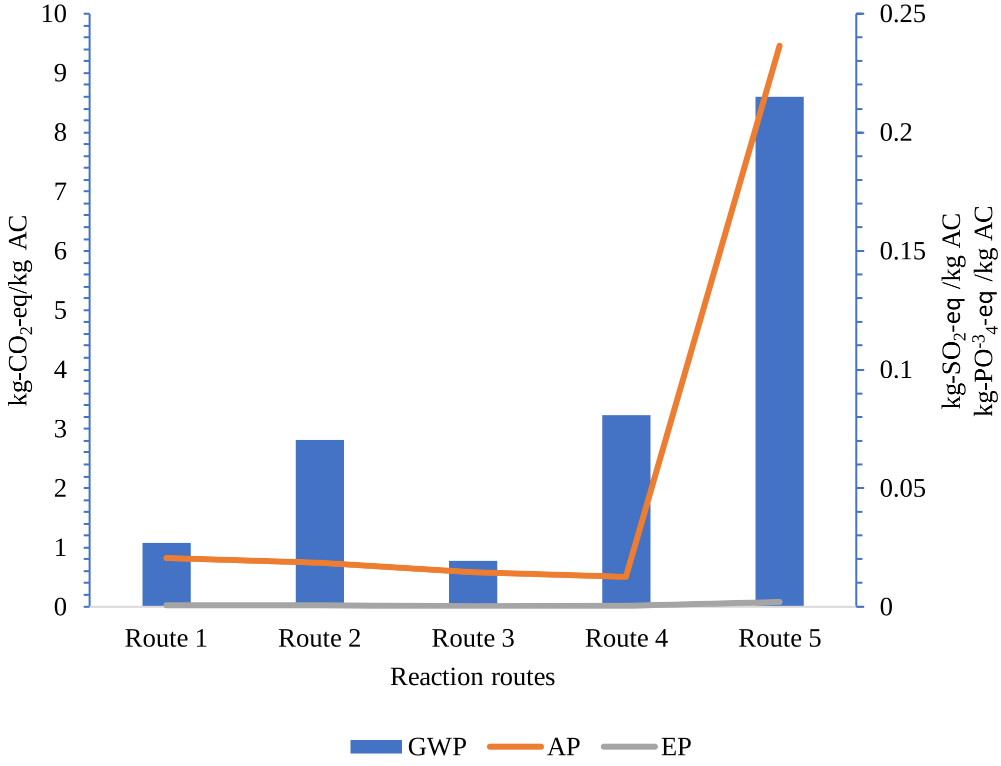

Fig. 10 Environmental impact of biomass-based activated carbon and coal-based activated carbon.

4 Conclusion

Evaluation of environmental impact for biomass-based activated carbon and coal activated carbon was conducted in terms of GWP, AP and EP. Generally, it was found that coal-based activated carbon has a significantly higher environmental impact compared to biomass-based activated carbon. Therefore, for a milder impact to the environment in terms of GWP, EP and AP, biomass-based activated carbon is a better option compared to coal-based activated carbon. In addition, biomass-based activated carbon is produced from renewable resource, whereby coal-based activated carbon is produced by non-renewable resource of fossil fuel. Utilizing the biomass waste as raw material for production of activated carbon also supports the expansion of circular economy. It is expected that this study would be able to provide a better understanding of environmental impacts associated with the conversion of biomass into activated carbon. This study can be further conducted by expanding the system boundary until the grave of the activated carbon, where with the environmental impact of different disposal method such as landfill, incineration, and regeneration could be considered. With that, we can obtain a more comprehensive environmental impact and choose the appropriate disposal method to dispose used activated carbon.

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Declaration of Conflict of Interest

The authors declared that there is no conflict of interest with any other party on the publication of the current work.

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