Comparative laboratory cost analysis of various activated carbon activation process

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Abstract. Activated carbon (AC) is an established adsorbent for organic pollutants reduction, metal removal, and liquid and gas adsorption. Cost analysis corresponds to determining the best approach for AC production depending on activation techniques with different degrees of activation is still minimal in literature. A cost estimation of AC production in laboratory scale using different conventional activation and post-activation surface modification process is performed in this study. This study attempts to develop a cost-friendly selection of activation process from laboratory scale prices. Chemicals and utility costs were acquired from vendor quotes (i.e., Sigma-Aldrich and Fisher Scientific) and Sarawak industrial electricity tariffs based on 100 g production. Oil palm-based ACs produced from five different activation or surface modification methods were compared to ascertain the least expensive production approach in terms of estimated production cost. Of the five methods investigated, method that quoted the least expensive production cost is chemical activation using potassium hydroxide (KOH) with minimum estimated cost of $7.30 whereas the most expensive production cost involves surface modification by polyethyleneimine (PEI) impregnation with cost of $873.00. Therefore, the estimated production cost for KOH activation is the minimum at $0.073 g⁻¹ while the maximum is $8.73 g⁻¹ for PEI impregnation.

Keywords: Oil palm-based activated carbon (AC); Laboratory scale; Activated carbon production; Production cost; Cost-friendly activation process

1. Introduction
Activated carbon (AC) is an established adsorbent for many different sectors of applications such as reduction of organic pollutants in water, metal removal, and liquid and gas adsorption [1–8]. Recently, oil palm has gain prominence as starting precursor for AC synthesis because it is abundantly available due to its substantial waste generated after harvesting, replanting, and crude oil production. It comprises of prominent compositions such as high carbon, high cellulose, high lignin, high nitrogen content, significant volatile material amount, and low ash content for further porous structure development [9–18]. Oil palm derived AC is extensively used in the applications of volatile organic compounds (VOC) removal, heavy metal reduction, wastewater treatment, flue gas purification, and the more recent carbon dioxide (CO₂) adsorption [6, 19–27].

ACs are synthesized through three types of activation process which are physical, chemical, and physiochemical activation. Physical activation is a method that uses an oxidizing gas (i.e., CO₂, steam,
or a binary mixture of gases) to activate the carbon enriched material (char) under elevated temperature (800-1100 °C) after the raw precursor is carbonized at mild temperature (400-600 °C) in an inert nitrogen (N₂) atmosphere [16, 19, 28–31]. In chemical activation, the raw precursor undergoes a chemical impregnation by soaking in a chemical solution which can be prepared from different medium (i.e., acidic (phosphoric acid (H₃PO₄) and sulphuric acid (H₂SO₄)), alkaline (potassium hydroxide (KOH) and sodium hydroxide (NaOH)), and transition metal salt, zinc chloride (ZnCl₂)), prior to the simultaneous carbonization and activation at temperature of 400-800 °C [32–37]. Physiochemical activation is a multi-sequences process which combines both chemical and physical activation to initially impregnate the raw precursor in the chemical solution, followed by high temperature (800-1000 °C) gasification by the oxidizing gas [19, 38–45].

In some works [46–52], to improve the surface chemistry of the resulting AC, the AC then further undergoes surface modification by nitrogen incorporation (i.e., ammonia (NH₃) treatment or amine incorporation) or metal salts functionalization, subsequently after the activation process. For NH₃ treatment, the AC is subjected to thermal treatment with the presence of NH₃ gas at an elevated temperature of 400-800 °C [49, 50]. The latter amine functionalization method is initially impregnating the AC in an amine-containing chemical solvent, followed by a mild temperature drying process [25, 48, 53]. In the metal salts functionalization method, the AC is soaked in a metal-containing chemical solvent, prior to high temperature heat treatment at 800 °C [46, 54].

There are some publications on the process scale-up for the AC manufacturing, leading to an estimation of pilot scale production costs. The scale-up of the process helps to identify and estimate the production cost for manufacturing the ACs at a commercial scale, which is used to determine their marketability. Among these are Toles et al. [55] which investigated the physical, chemical, and adsorption properties of a series of unoxidized/oxidized, steam or CO₂-activated almond shell carbons via six different activation or activation/oxidation conditions for each series and their estimated production cost, followed by a comparison with commercial carbons to determine best physical activation method and the least expensive for manufacturing the almond shell derived GAC. Lima et al. [56] developed an estimation of conceptual capital and operating cost using Superpro Designer process simulation.

A series of H₃PO₄-activated almond shell carbons prepared from six different conditions of activation or activation/oxidation methods were investigated and compared to two commercial carbons by Toles et al. [57] to ascertain their relative value in terms of yield, physical, chemical, and adsorption properties, as well as the estimated production cost based on scale-up of processes to determine their commercial viability. Ng et al. [58] evaluated a cost estimation for manufacturing pecan shell-based carbons using steam or H₃PO₄ activation at a large-scale production, based on the developed process flow diagrams. Influence of different types of activating agent (i.e., H₃PO₄ and KOH), impregnation ratios, and carbonization temperatures on the properties of the synthesized AC which prepared from Persian Ironwood biomass, their CO₂ adsorption performance and the capital cost estimation of the final production were investigated by Nowrouzi et al. [59]. Other than the above-mentioned research works, comprehensive research work of the estimation of production cost for producing AC from oil palm biomass is not yet available.

Therefore, this present study aims to evaluate the production cost at laboratory scale of oil palm-based AC prepared from five different activation or post-activation surface modification methods. A comparison is made between these five activation or surface modification methods to determine the least expensive process to produce the oil palm-based ACs at the same basis of yield (100 g).

2. Methodology

Costs for the five types of activation and post-activation surface modification methods are developed taking on a basis of 100 g production of oil palm-based AC, based on the process conditions presented in earlier research works. A comparative assessment was performed to identify and select the least expensive process from each activation/modification method that is presented with the lowest production/modification cost.
2.1. Materials

Raw oil palm wastes (i.e., oil palm shell, oil palm empty fruit bunch, oil palm frond, oil palm trunk, oil palm fiber, and oil palm seed) available from a local oil palm plantation and palm oil mill as the precursor. Carbon dioxide (CO₂, 0.01-99.80%, Fisher Scientific) and steam (H₂O, Fisher Scientific) are the oxidizing gas for AC via physical and physiochemical activation. Dehydrating agent such as phosphoric acid (H₃PO₄, ≥ 85 wt. % in water, Sigma-Aldrich), sulphuric acid (H₂SO₄, 95.0-98.0%, Sigma-Aldrich), zinc chloride (ZnCl₂, ≥ 98%, Sigma-Aldrich), potassium hydroxide (KOH, 0.1 N or ≥ 85%, Sigma-Aldrich), potassium carbonate (K₂CO₃, ≥ 99.0%, Sigma-Aldrich), and sodium hydroxide (NaOH, 0.1 N, 50% in water, 97%, or ≥ 98%, Sigma-Aldrich) are the activating agent for AC preparation by chemical and physiochemical activation. The modifying agent are polyethyleneimine (PEI, 50 wt% in water, Sigma-Aldrich), 2-amino-2-methyl-1-propanol (AMP, 90% with ~5% water, Sigma-Aldrich), 2-amino-2-methyl-1,3-propanediol (AMPD, ≥ 99%, Sigma-Aldrich), 2-(methylamino)ethanol (MMEA, ≥ 98%, Sigma-Aldrich), mono-ethanolamine (MEA, ≥ 99.0%, Sigma-Aldrich), diethanolamine (DEA, ≥ 98.0%, Sigma-Aldrich), ethylenediamine (EDA, ≥ 99.0%, Sigma-Aldrich), diethylenetriamine (DETA, 99%, Sigma-Aldrich), nickel nitrate hexahydrate (Ni(NO₃)₂·6H₂O, Sigma-Aldrich), ammonia metavanadate (NH₄VO₃, 99%, Sigma-Aldrich), ferum nitrate (Fe(NO₃)₃·9H₂O, ≥ 98%, Sigma-Aldrich), cerium nitrate (Ce(NO₃)₃·6H₂O, 99%, Sigma-Aldrich), barium oxide (BaO, 97%, Sigma-Aldrich), magnesium oxide (MgO, 97%, Sigma-Aldrich), copper oxide (CuO, ≥ 99.0%, Sigma-Aldrich), titanium oxide (TiO₂, ≥ 99.0%, Sigma-Aldrich), and cerium oxide (CeO₂, 90% or ≥ 99.0%, Sigma-Aldrich) for surface chemistry modification of the AC. The commercially available methanol (CH₃OH, 99.80%, Sigma-Aldrich) and toluene (C₇H₈, 99.80%, Sigma-Aldrich) as solvent for the modifying agent.

2.2. Activation or post-activation surface modification methods

The procedure and process of oil palm wastes ACs through activation or post-activation surface modification are described by earlier research works [5, 6, 8, 19, 23, 25, 29, 41, 46–48, 52–54, 60–72]. These works shown that AC are produced via physical activation using CO₂ and steam, chemical activation using H₃PO₄, H₂SO₄, ZnCl₂, KOH, K₂CO₃, and NaOH or physiochemical activation through the combination of chemical and physical activation, using either one-stage or two-stage process by furnace-heating or microwave-heating. The one-stage process carried out simultaneously carbonization and activation process at temperature of 500-1000 °C whereas two-stage process initially carbonized the starting precursor at temperature ranging between 100 °C and 1200 °C to produce carbon-enriched material (char), followed by heat treatment at temperature of 500-1100 °C. The final activated materials then undergo subsequent surface modification through amine (i.e., PEI solution, AMP, AMPD, MMEA, MEA, DEA, EDA, and DETA) or metal (i.e., Ni(NO₃)₂·6H₂O, NH₄VO₃, Fe(NO₃)₃·9H₂O, Ce(NO₃)₃·6H₂O, BaO, MgO, CuO, TiO₂, and CeO₂) impregnation to alter and improve their surface functional groups. The various activation and subsequent surface modification processes for the oil palm-based AC are illustrated in figure 1.
Figure 1. Schematic diagram of a complete activation and subsequent surface modification procedure for oil palm-based AC.

2.3. Determination of cost-effective activation process
Preparation conditions and activities performed in earlier research works [5, 6, 8, 19, 23, 25, 29, 41, 46–48, 52–54, 60–72] without reference to laboratory scale activation carbon production cost estimation method are referred in the evaluation for oil palm-derived AC production cost. The estimation of cost is evaluated for the activation of char after carbonization or starting precursor through physical (CO₂ and
steam), chemical (H₃PO₄, H₂SO₄, ZnCl₂, KOH, K₂CO₃, and NaOH), and physiochemical activation, as well as post-activation surface modification of final activated materials by nitrogen incorporation using amine-based chemical solvent and metal salts impregnation. The laboratory scale production cost estimates were developed on a basis of 100 g ACs produced from each activation/surface modification method. Consumable pricing came from budgetary consumable quotations from vendors such as Sigma-Aldrich and Fisher Scientific. Utility requirements were calculated from local electricity provider (Sarawak Energy Berhad) electricity tariffs for industrial. The power consumptions for operating equipment: orbital shaker, drying oven, Soxhlet extraction, electric furnace, and microwave oven used for the production processes for agitation, drying, solvent reflux, and activation are 5.7, 2400, 200, 1000, and 1400 W, respectively. Each activation or post-activation surface modification process estimated production cost was then compared to select the more cost-friendly method. There are 14 methods of activation and post-activation surface modification investigated in this study with the respective commodity chemical (oxidizing gas), chemical agent or modifying agent used and operational time of each process presented in Table 1.
Table 1. Activation and post-activation surface modification methods process parameters for oil palm waste-based ACs production used to estimate the laboratory scale production cost (Reproduced from [5, 6, 8, 19, 23, 25, 29, 41, 46–48, 52–54, 60–70]).

| Method                        | Heat treatment conditions | Pre-activation activity | Post-activation treatment |
|-------------------------------|---------------------------|-------------------------|---------------------------|
|                               | Carbonization time (h)    | Gas/Chemical            | Activiation time (h)      | Drying time (h) | Agitation time (h) | Agitation with heating (h) | Drying time (h) | Solvent reflux (h) | Thermal treatment time (h) |
| (I) Physical activation      |                           |                         |                           |                |                    |                                |                |                    |                                |
|                               | 0.5-3                     | CO₂                     | 1-3                       | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     |
|                               | 0.5-2                     | Steam                   | 0.5-7                     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     |
| (II) Chemical activation     |                           |                         |                           |                |                    |                                |                |                    |                                |
| NA<sup>a</sup>               | H<sub>3</sub>PO<sub>4</sub> | 2                       | 24                       | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     |
| NA<sup>a</sup>               | H<sub>2</sub>SO<sub>4</sub> | 2                       | 24                       | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     |
| NA<sup>a</sup>               | ZnCl<sub>2</sub>          | 1-2                     | 24                       | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     |
| 0.33-5                       | KOH                       | 0.083-2                 | 24                       | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     |
| NA<sup>a</sup>               | K<sub>2</sub>CO<sub>3</sub> | 1-2                     | 24                       | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     |
| 0.5                          | NaOH                      | 1                       | 24                       | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     |
| 2                            | H<sub>3</sub>PO<sub>4</sub> and CO<sub>2</sub> | 1-7                     | 24                       | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     |
| 1                            | H<sub>2</sub>SO<sub>4</sub> and CO<sub>2</sub> | 1                       | 24                       | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     |
| 2                            | ZnCl<sub>2</sub> and CO<sub>2</sub> | 1-7                     | 24                       | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     |
| 2-5                          | KOH and CO<sub>2</sub>    | 1-2                     | 24                       | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     |
| 1-2                          | NaOH and CO<sub>2</sub>   | 1.5-3                   | 24                       | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     | NA<sup>a</sup>     |
| Method                                      | Heat treatment conditions | Pre-activation activity | Post-activation treatment |
|--------------------------------------------|---------------------------|-------------------------|---------------------------|
|                                            | Carbonization time (h)    | Gas/Chemical            | Activation time (h)       | Drying time (h) | Agitation time (h) | Agitation with heating (h) | Drying time (h) | Solvent reflux (h) | Thermal treatment time (h) |
|                                            |                           |                         |                           |               |                  |                             |               |                  |                          |
| (IV) Post-activation surface modification by amine incorporation | NA<sup>a</sup>           | PEI solution            | NA<sup>a</sup>            | NA<sup>a</sup> | 72                | NA<sup>a</sup>               | 24             | NA<sup>a</sup>      | NA<sup>a</sup>              |
|                                            | NA<sup>a</sup>           | AMPD                    | NA<sup>a</sup>            | NA<sup>a</sup> | 24                | NA<sup>a</sup>               | 24             | NA<sup>a</sup>      | NA<sup>a</sup>              |
|                                            | NA<sup>a</sup>           | AMP                     | NA<sup>a</sup>            | NA<sup>a</sup> | 24                | NA<sup>a</sup>               | 24             | NA<sup>a</sup>      | NA<sup>a</sup>              |
|                                            | NA<sup>a</sup>           | MMEA                    | NA<sup>a</sup>            | NA<sup>a</sup> | 24                | NA<sup>a</sup>               | 24             | NA<sup>a</sup>      | NA<sup>a</sup>              |
|                                            | NA<sup>a</sup>           | MEA                     | NA<sup>a</sup>            | NA<sup>a</sup> | 24                | NA<sup>a</sup>               | 24             | NA<sup>a</sup>      | NA<sup>a</sup>              |
|                                            | NA<sup>a</sup>           | MEA in methanol         | NA<sup>a</sup>            | NA<sup>a</sup> | 24                | NA<sup>a</sup>               | 24             | NA<sup>a</sup>      | NA<sup>a</sup>              |
|                                            | NA<sup>a</sup>           | DEA in Methanol         | NA<sup>a</sup>            | NA<sup>a</sup> | 24                | NA<sup>a</sup>               | 24             | NA<sup>a</sup>      | NA<sup>a</sup>              |
|                                            | NA<sup>a</sup>           | EDA solution in toluene  | NA<sup>a</sup>            | NA<sup>a</sup> | 24                | NA<sup>a</sup>               | 24             | 4                 | NA<sup>a</sup>              |
|                                            | NA<sup>a</sup>           | DETA solution in toluene | NA<sup>a</sup>            | NA<sup>a</sup> | 24                | NA<sup>a</sup>               | 24             | 4                 | NA<sup>a</sup>              |
|                                            | NA<sup>a</sup>           | Pure EDA                | NA<sup>a</sup>            | NA<sup>a</sup> | 24                | NA<sup>a</sup>               | 24             | 4                 | NA<sup>a</sup>              |
|                                            | NA<sup>a</sup>           | Pure DETA               | NA<sup>a</sup>            | NA<sup>a</sup> | 24                | NA<sup>a</sup>               | 24             | 4                 | NA<sup>a</sup>              |
| Method                                      | Heat treatment conditions | Pre-activation activity | Post-activation treatment |
|---------------------------------------------|---------------------------|-------------------------|----------------------------|
| Carbonization time (h)                      | Gas/Chemical              | Activation time (h)     | Drying time (h)   | Agitation time (h) | Agitation with heating (h) | Drying time (h) | Solvent reflux (h) | Thermal treatment time (h) |
| Pre-activation activity                     |                           |                         |               |                  |                           |               |                   |                              |
| Post-activation treatment                   |                           |                         |               |                  |                           |               |                   |                              |
| Carbonization time (h)                      | Gas/Chemical              | Activation time (h)     | Drying time (h)   | Agitation time (h) | Agitation with heating (h) | Drying time (h) | Solvent reflux (h) | Thermal treatment time (h) |
| (V) Post-activation surface modification by metal impregnation | NA a | Nickel nitrate hexahydrate (Ni(NO$_3$)$_2$·6H$_2$O) | NA a | NA a | NA a | 5.33 | 12 | NA a | 4 |
|                                              | NA a | Ammonia metavanadate (NH$_4$VO$_3$) | NA a | NA a | NA a | 5.33 | 12 | NA a | 4 |
|                                              | NA a | Ferum nitrate (Fe(NO$_3$)$_3$·9H$_2$O) | NA a | NA a | NA a | 5.33 | 12 | NA a | 4 |
|                                              | NA a | Cerium nitrate (Ce(NO$_3$)$_3$·6H$_2$O) | NA a | NA a | NA a | 5.33 | 12 | NA a | 4 |
|                                              | NA a | Barium oxide (BaO) | NA a | NA a | NA a | NA a | 24 | NA a | 1 |
|                                              | NA a | Magnesium oxide (MgO) | NA a | NA a | NA a | NA a | 24 | NA a | 1 |
|                                              | NA a | Copper oxide (CuO) | NA a | NA a | NA a | NA a | 24 | NA a | 1 |
|                                              | NA a | Titanium oxide (TiO$_2$) | NA a | NA a | NA a | NA a | 24 | NA a | 1 |
|                                              | NA a | Cerium oxide (CeO$_2$) | NA a | NA a | NA a | NA a | 24 | NA a | 1 |

a NA = Not available in the specific activation/post-activation surface modification process.
3. Results and Discussion

3.1. Activation and surface modification process cost analysis

3.1.1. Physical activation of oil palm waste. A cost analysis of physically AC production via CO₂ and steam activation using different percent concentration of CO₂ is summarized in table 2. A comparison of estimated production cost among these physically ACs produced using two different types of activating agents were studied.

| Item | Unit Cost ($) | Amount | Total cost ($) |
|------|--------------|--------|---------------|
| **Consumables** | | | |
| CO₂ 99.80% (48 L) | 826.00 | 3-15 L | **51.60-258.10** |
| CO₂ 0.01% in N₂ (48 L) | 1257.20 | 3-15 L | 78.60-392.90 |
| CO₂ 0.1% in N₂ (48 L) | 1446.40 | 3-15 L | 90.40-452.00 |
| CO₂ 0.5% in carbon monoxide (CO) 0.5%, hydrogen (H₂) 0.5%, oxygen (O₂) 0.5% with N₂ balanced (48 L) | 1589.50 | 3-15 L | 99.40-496.70 |
| CO₂ 1% in CO 1%, H₂ 1%, O₂ 1% with N₂ balanced (48 L) | 1762.50 | 3-15 L | 110.20-550.80 |
| CO₂ 15% in CO 7%, O₂ 4%, CH₄ 4.5% with N₂ balanced (48 L) | 1517.90 | 3-15 L | 94.90-474.40 |
| Steam (CO 7%, O₂ 4%, CO₂ 15%, CH₄ 4.5% in N₂, 48 L) | 1517.90 | 4.5-24 L | 142.30-759.00 |
| **Utilities cost** | | | |
| Electricity | $0.056 kWh⁻¹ | 1-11.2 kWh | 0.056-0.63 |

<sup>a</sup> Value in **bold** indicates minimum value for physical activation of AC production cost.

The raw oil palm biomass is available at no cost and utilized as starting materials for AC production. Hence, the purchased price of the raw oil palm biomass is not included in the cost study. Based on table 2, physical activation carried out using CO₂ in pure form with high purity of 99.80% has the minimum estimated production cost range of $51.70-258.50. Compared to CO₂-AC production, production of steam-activated oil palm carbon gave the maximum estimated production cost range of $142.40-759.60 among the physical activation productions. This manifests that steam activation has higher cost for AC production compared to CO₂ activation, given its higher activating agent consumption required in the activation. The estimated product cost is $0.52-2.59 g⁻¹ for CO₂-activated oil palm carbon using pure CO₂ whereas $1.42-7.60 g⁻¹ for steam-AC.
3.1.2. Chemical activation of oil palm waste. Cost analysis for chemical activation of oil palm waste in laboratory scale using various dehydrating agent (i.e., H₃PO₄, H₂SO₄, ZnCl₂, KOH, K₂CO₃, and NaOH) as activating agent is summarized in Table 3. Similar to the cost analysis for physical activation of oil palm wastes, the purchased price for the raw oil palm biomass is not included in the cost study given the raw oil palm biomass is obtained from plantation without charge. Similar assignment is taken in the cost study for physiochemical activation of oil palm waste and post-activation surface modification of oil palm-based ACs. Comparison of the estimated production cost among the oil palm-based ACs produced via chemical activation is studied.

Table 3. Operating costs for laboratory chemical activation of oil palm waste [79–89].

| Item                        | Unit Cost ($) | Amount | Total cost ($) |
|-----------------------------|--------------|--------|----------------|
| **Consumables**             |              |        |                |
| H₃PO₄ ≥ 85 wt.% in water    | 153.00       | 0.20 L | 12.20          |
| (2.5 L)                     |              |        |                |
| H₂SO₄ 95.0-98.0% (2.5 L)    | 85.70        | 0.20 L | 6.90           |
| ZnCl₂ ≥ 98% (500 g)         | 94.00        | 30 g   | 5.60           |
| KOH 0.1 M in water (0.1 N), | 37.90        | 0.20 L | 7.60           |
| solution (1 L)              |              |        |                |
| KOH ≥ 85%, pellets (500 g)  | 43.20        | 30 g   | **2.60**a      |
| K₂CO₃ ≥ 99.0% (500 g)       | 48.80        | 30 g   | 2.90           |
| NaOH ≥ 98%, pellets, anhydrous (500 g) | 60.70 | 30 g | 3.60 |
| NaOH 97%, powder (500 g)    | 262.00       | 30 g   | 15.70          |
| NaOH 0.1 M in water (0.1 N) (1 L) | 38.40 | 0.20 L | 7.70 |
| NaOH 50% in water (1 L)     | 55.50        | 0.20 L | 11.10          |
| **Utilities cost**          |              |        |                |
| Electricity                 | $0.056 kWh⁻¹ | 84.4-98.8 kWh | 4.70-5.50 |

*Value in bold indicates minimum value for chemical activation of AC production cost.*

Based on Table 3, minimum production cost of $7.30-8.10 was estimated for chemical activation of oil palm wastes using KOH activating agent with high purity of ≥ 85%, given its low chemical price required for activation. While, conversely, chemical activation with NaOH (97% purity) offers the highest production cost ranging from $20.60 to $21.20. High purchased chemical price for NaOH
attributes to a slightly larger amount of cost for production. The estimated product cost for KOH-AC with the use of KOH, ≥ 85% purity is $0.073-0.081 g⁻¹ and NaOH-AC by NaOH, 97% purity is estimated up to $0.21 g⁻¹.

3.1.3. Physiochemical activation of oil palm waste. Physicochemical activation is performed through different combinations of chemical and physical activation. Different combination presents different amount of cost for production. Types of chemical agent, types of oxidizing gas, and their respective purchased price are significant factors that affect the estimation on production cost. Various physiochemical combination and their respective estimated production cost are summarized in table 4 and compared based on their maximum production cost to determine the physiochemical combination which gives minimum production cost.

Based on table 4, physiochemical combination of chemical activation using various chemical agents (i.e., H₃PO₄, H₂SO₄, ZnCl₂, KOH or NaOH) with physical activation using CO₂ in gas mixture with high concentration from 0.5% to 15% cost higher with estimation at $102.60-132.10 compare to combination with low concentration CO₂ (0.01% and 0.1%) in N₂ at $86.30-112.30 and pure CO₂ (99.80% purity) at $59.40-73.50. The estimated production cost for physiochemical activation with acidic dehydrating agents (H₃PO₄ and H₂SO₄) and CO₂ in gas mixture with high concentration range from $106.70 up to $129.70. Conversely, AC production through physiochemical activation using combination of alkaline chemicals (KOH and NaOH) and CO₂ in gas mixture with high concentration shows an estimated production cost that ranges from $102.60 up to $132.10. Activation with both ZnCl₂ and high concentration CO₂ in gas mixture requires a production cost of $105.70-123.10. The high purchased chemical price of NaOH ($38.40-262.00) is the principal contribution to the highest production cost in the physiochemical combination of alkaline chemicals and high concentration of CO₂ in gas mixture than the other physiochemical combinations. Therefore, the overall range of the estimated cost for physiochemically AC would be $0.59-1.32 g⁻¹.
Table 4. Summary of operating costs for laboratory physiochemical activation of oil palm biomass [73–89].

| Utility        | Unit cost ($)/kWh | Amount  | Total cost ($)  |
|----------------|-------------------|---------|-----------------|
| Electricity    | $0.056-0.058      | 88.4-125.4 kWh | 5.00-7.30       |

| Dehydrating agent | Activating agent | Combination     | (1) H₃PO₄ | (2) H₂SO₄ | (3) ZnCl₂ | (4) KOH | (5) NaOH |
|-------------------|------------------|----------------|-----------|-----------|-----------|---------|----------|
|                   | (1) CO₂ 99.80% (48 L) | 69.00-71.10 | 63.40-64.00 | **62.40-64.50** | 59.40-65.40 | 60.50-73.50 |
|                   | (2) CO₂ 0.01% in N₂ (48 L) | 96.00-98.10 | 90.40-91.00 | 89.40-91.50 | 86.30-92.30 | 87.50-100.50 |
|                   | (3) CO₂ 0.1% in N₂ (48 L) | 107.80-109.90 | 102.20-102.80 | 101.20-103.30 | 98.10-104.20 | 99.30-112.30 |
|                   | (4) CO₂ 0.5% in carbon monoxide (CO) 0.5%, hydrogen (H₂) 0.5%, oxygen (O₂) 0.5% with N₂ balanced (48 L) | 116.70-118.90 | 111.20-111.70 | 110.10-112.30 | 107.10-113.10 | 108.20-121.20 |
|                   | (5) CO₂ 1% in CO 1%, H₂ 1%, O₂ 1% with N₂ balanced (48 L) | 127.50-129.70 | 122.00-122.50 | 120.90-123.10 | 117.90-123.90 | 119.00-132.10 |
|                   | (6) CO₂ 15% in CO 7%, O₂ 4%, CH₄ 4.5% with N₂ balanced (48 L) | 112.30-114.40 | 106.70-107.30 | 105.70-107.80 | 102.60-108.60 | 103.80-116.80 |

*Value in bold indicates minimum value for physiochemical activation of AC production cost.
3.1.4. Surface modification of oil palm waste-based AC. Surface modification of oil palm waste-based AC is usually performed through the incorporation of amine or metal on the resulting AC obtained from the activation process. A cost study is developed at a given purchased chemical prices of 100 g physically, chemically and physiochemically ACs (table 5), the purchased chemical prices for chemical solvents (methanol (CH$_3$OH) and toluene (C$_7$H$_8$)), amine-functionalizing doping agents (i.e., PEI solution, AMP, AMPD, MMEA, MEA, DEA, EDA, and DETA), and metal-functionalizing doping agents (i.e., Ni(NO$_3$)$_2$·6H$_2$O, NH$_4$VO$_3$, Fe(NO$_3$)$_3$·9H$_2$O, Ce(NO$_3$)$_3$·6H$_2$O, BaO, MgO, CuO, TiO$_2$, and CeO$_2$) and the utility costs (table 6 and 7) to estimate the modification cost of amine/metal-functionalized ACs. A summary of modification costs for various modification incorporation are tabulated in table 6 and 7 and compared based on their maximum value in the range of total estimated modification cost to determine the least expensive modification process.

**Table 5.** Summary of chemical costs for laboratory surface modification of oil palm waste-based AC [90–109].

| Item | Unit Cost ($) | Amount | Total cost ($) |
|------|---------------|--------|----------------|
| **Consumables** | | | |
| PEI solution 50 wt% in H$_2$O (1 L) | 200.00 | 0.50 L | 100.00 |
| AMP 90% with ~5% water (1 L) | 57.70 | 0.50 L | 28.90 |
| AMPD ≥ 99% (500 g) | 259.00 | 2 g | 1.00 |
| MMEA ≥ 98% (2 L) | 79.40 | 0.50 L | 19.90 |
| MEA ≥ 99.0% (2.5 L) | 175.00 | 0.50 L | 35.00 |
| CH$_3$OH ≥ 99.80% (1 L) | 67.10 | 0.005 L | 0.30 |
| DEA ≥ 98.0% (500 g) | 40.50 | 2 L | 0.20 |
| EDA ≥ 99.0% (2.5 L) | 127.00 | 0.50 L | 25.40 |
| C$_7$H$_8$ 99.80% (1 L) | 65.50 | 0.005 L | 0.30 |
| DETA 99% (2.5 L) | 124.00 | 0.50 L | 24.80 |
| Ni(NO$_3$)$_2$·6H$_2$O (500 g) | 104.00 | 2 g | 0.40 |
| NH$_4$VO$_3$ 99% (1000 g) | 304.00 | 2 g | 0.60 |
| Fe(NO$_3$)$_3$·9H$_2$O ≥ 98% (500 g) | 83.90 | 2 g | 0.30 |
| Item                                           | Unit Cost ($) | Amount | Total cost ($) |
|------------------------------------------------|---------------|--------|----------------|
| Ce(NO$_3$)$_3$·6H$_2$O 99% (500 g)             | 267.00        | 2 g    | 1.10           |
| BaO 97% (250 g)                               | 396.00        | 25 g   | 39.60          |
| MgO 97% (500 g)                               | 484.00        | 50 g   | 48.40          |
| CuO ≥ 99.0% (100 g)                           | 66.10         | 10 g   | 6.60           |
| TiO$_2$ ≥ 99.0% (1000 g)                      | 69.30         | 100 g  | 6.90           |
| CeO$_2$ ≥ 99.0% (100 g)                       | 51.80         | 10 g   | 5.20           |
| CeO$_2$, 99.995% trace metals basis, powder (50 g) | 468.00       | 5 g    | 46.80          |
| Materials                                     |               |        |                |
| CO$_2$-AC (100 g)                              | 51.70-551.20  | 100 g  | 51.70-551.20   |
| Steam-AC (100 g)                              | 142.40-759.60 | 100 g  | 142.40-759.60  |
| H$_3$PO$_4$-AC (100 g)                         | 17.20-17.80   | 100 g  | 17.20-17.80    |
| H$_2$SO$_4$-AC (100 g)                         | 11.80-12.40   | 100 g  | 11.80-12.40    |
| ZnCl$_2$-AC (100 g)                            | 10.40-11.20   | 100 g  | 10.40-11.20    |
| KOH-AC (100 g)                                 | 7.30-13.10    | 100 g  | 7.30-13.10     |
| K$_2$CO$_3$-AC (100 g)                         | 7.70-8.50     | 100 g  | 7.70-8.50      |
| NaOH-AC (100 g)                                | 8.50-21.20    | 100 g  | 8.50-21.20     |
| H$_3$PO$_4$, CO$_2$-AC (100 g)                 | 69.00-129.70  | 100 g  | 69.00-129.70   |
| H$_2$SO$_4$, CO$_2$-AC (100 g)                 | 63.40-122.50  | 100 g  | 63.40-122.50   |
| ZnCl$_2$, CO$_2$-AC (100 g)                    | 62.40-123.10  | 100 g  | 62.40-123.10   |
| KOH, CO$_2$-AC (100 g)                         | 59.40-123.90  | 100 g  | 59.40-123.90   |
Table 6 and 7 present the estimated surface modification cost for the various amine/metal incorporation combination of AC. It can be seen from table 6 that PEI functionalization of steam-activated oil palm carbon requires the highest modification cost of $255.80-873.00, while DEA functionalization of K$_2$CO$_3$-activated oil palm carbon in methanol (CH$_3$OH), conversely, is estimated at lower modification cost of $14.90-15.70. High purchased chemical prices for steam-activated oil palm carbon ($142.40-759.60) and high utility cost ($13.40) for prolonged process operation attributes the PEI functionalization steam-activated oil palm carbon the highest estimated modification cost. The estimated product cost for PEI-functionalized steam-activated oil palm carbon and DEA-functionalized K$_2$CO$_3$-activated oil palm carbon is $2.56-8.73 \text{ g}^{-1}$ and $0.15-0.16 \text{ g}^{-1}$, respectively.

Comparing to the metal incorporation of oil palm-based AC, as seen in table 7, a modification cost is estimated at $195.70-812.80 for MgO functionalization steam-activated oil palm carbon whereas a lower modification cost of $11.90-12.50 is required for ferum nitrate (Fe(NO$_3$)$_3$·9H$_2$O) functionalization K$_2$CO$_3$-activated oil palm carbon. The MgO functionalization steam-activated oil palm carbon gives the highest modification cost due to high purchased chemical prices for the metal-functionalizing doping agent, MgO and the steam-AC. The estimated product cost for MgO-functionalized steam-activated oil palm carbon is $1.96-8.13 \text{ g}^{-1}$ while $0.12-0.13 \text{ g}^{-1}$ for Fe(NO$_3$)$_3$·9H$_2$O-functionalized K$_2$CO$_3$-activated oil palm carbon.

| Item | Unit Cost ($) | Amount | Total cost ($) |
|------|---------------|--------|----------------|
| NaOH, CO$_2$-AC (100 g) | 60.50-132.10 | 100 g | 60.50-132.10 |
| Range | | | 571.70-2026.30 |
Table 6. Summary of operating costs for laboratory amine incorporation of oil palm biomass-derived AC [79, 90–99].

| Utility | Unit cost ($) | Amount | Total cost ($) |
|---------|---------------|--------|----------------|
| Electricity | $0.056-0.058 kWh$ | 72.8-231.4 kWh | 4.10-13.40 |

Total surface modification cost ($)

| Modifying agent | Incorporation | (1) PEI solution | (2) AMP | (3) AMPD | (4) MMEA | (5) MEA |
|-----------------|---------------|------------------|--------|---------|---------|--------|
| Activated carbon (AC) | CO$_2$-AC | 165.10-664.60 | 87.20-586.70 | 59.40-558.90 | 78.20-577.70 | 93.40-592.90 |
| | Steam-AC | 255.80-873.00 | 178.00-795.20 | 150.10-767.30 | 169.00-786.20 | 184.10-801.30 |
| | H$_3$PO$_4$-AC | 130.60-131.20 | 52.80-53.30 | 24.90-25.50 | 43.80-44.30 | 58.90-59.50 |
| | H$_2$SO$_4$-AC | 125.20-125.80 | 47.40-48.00 | 19.60-20.10 | 38.40-39.00 | 53.50-54.10 |
| | ZnCl$_2$-AC | 123.80-124.60 | 46.00-46.70 | 18.20-18.90 | 37.00-37.70 | 52.10-52.90 |
| | KOH-AC | 120.70-126.50 | 42.90-48.70 | 15.10-20.90 | 33.90-39.70 | 49.00-54.80 |
| | K$_2$CO$_3$-AC | 121.10-121.90 | 43.30-44.00 | 15.40-16.20 | 34.30-35.00 | 49.40-50.20 |
| | NaOH-AC | 121.90-134.60 | 44.10-56.70 | 16.20-28.90 | 35.10-47.70 | 50.20-62.90 |
| | H$_3$PO$_4$, CO$_2$-AC | 182.40-243.10 | 104.60-165.20 | 76.80-137.40 | 95.60-156.20 | 110.70-171.40 |
| | H$_2$SO$_4$, CO$_2$-AC | 176.90-236.00 | 99.00-158.10 | 71.20-130.30 | 90.00-149.10 | 105.10-164.30 |
| | ZnCl$_2$, CO$_2$-AC | 175.80-236.50 | 98.00-158.60 | 70.20-130.80 | 89.00-149.60 | 104.10-164.80 |
| | KOH, CO$_2$-AC | 172.80-237.30 | 94.90-159.50 | 67.10-131.70 | 85.90-150.50 | 101.10-165.60 |
| | NaOH, CO$_2$-AC | 173.90-245.50 | 96.10-167.60 | 68.30-139.80 | 87.10-158.60 | 102.20-173.80 |
Table 6 (continued).

| Utility | Unit cost ($) | Amount | Total cost ($) |
|---------|---------------|--------|----------------|
| Electricity | $0.056-0.058 kWh<sup>-1</sup> | 72.8-231.4 kWh | 4.10-13.40 |

| Modifying agent | Incorporation | (6) MEA in CH<sub>3</sub>OH | (7) DEA in CH<sub>3</sub>OH | (8) EDA | (9) EDA in C<sub>7</sub>H<sub>8</sub> | (10) DETA | (11) DETA in C<sub>7</sub>H<sub>8</sub> |
|-----------------|---------------|----------------------------|---------------------------|--------|----------------------------|---------|----------------------------|
| AC              | (1) CO<sub>2</sub>-AC | 93.70-593.20 | 58.90-558.40 | 81.20-580.60 | 81.50-584.10 | 80.60-580.00 | 80.90-583.50 |
|                 | (2) Steam-AC | 184.40-801.60 | 149.60-766.80 | 171.90-789.10 | 175.40-792.60 | 171.30-788.50 | 174.80-792.00 |
|                 | (3) H<sub>3</sub>PO<sub>4</sub>-AC | 59.20-59.80 | 24.40-25.00 | 46.70-47.30 | 50.20-50.70 | 46.10-46.70 | 49.60-50.10 |
|                 | (4) H<sub>2</sub>SO<sub>4</sub>-AC | 53.90-54.40 | 19.00-19.60 | 41.30-41.90 | 44.80-45.40 | 40.70-41.30 | 44.20-44.80 |
|                 | (5) ZnCl<sub>2</sub>-AC | 52.40-53.20 | 17.60-18.40 | 39.90-40.70 | 43.40-44.10 | 39.30-40.10 | 42.80-43.50 |
|                 | (6) KOH-AC | 49.40-55.20 | 14.50-20.30 | 36.80-42.60 | 40.30-46.10 | 36.20-42.00 | 39.70-45.50 |
|                 | (7) K<sub>2</sub>CO<sub>3</sub>-AC | 49.70-50.50 | 14.90-15.70 | 37.20-37.90 | 40.70-41.40 | 36.60-37.30 | 40.10-40.80 |
|                 | (8) NaOH-AC | 50.50-63.20 | 15.70-28.40 | 38.00-50.60 | 41.50-54.10 | 37.40-50.00 | 40.90-53.50 |
|                 | (9) H<sub>3</sub>PO<sub>4</sub>, CO<sub>2</sub>-AC | 111.10-171.70 | 76.20-136.90 | 98.50-159.20 | 102.00-162.60 | 97.90-158.60 | 101.40-162.00 |
|                 | (10) H<sub>2</sub>SO<sub>4</sub>, CO<sub>2</sub>-AC | 105.50-164.60 | 70.60-129.80 | 92.90-152.00 | 96.40-155.50 | 92.30-151.40 | 95.80-154.90 |
|                 | (11) ZnCl<sub>2</sub>, CO<sub>2</sub>-AC | 104.50-165.10 | 69.60-130.30 | 91.90-152.60 | 95.40-156.00 | 91.30-152.00 | 94.80-155.40 |
|                 | (12) KOH, CO<sub>2</sub>-AC | 101.40-166.00 | 66.60-131.10 | 88.80-153.40 | 92.30-156.90 | 88.20-152.80 | 91.70-156.30 |
|                 | (13) NaOH, CO<sub>2</sub>-AC | 102.50-174.10 | 67.70-139.30 | 90.00-161.50 | 93.50-165.00 | 89.40-160.90 | 92.90-164.40 |

*Value in bold indicates minimum value for surface modification of AC cost.*
Table 7. Summary of operating costs for laboratory metal incorporation of oil palm biomass-derived AC [79, 100–109].

| Utility   | Unit cost ($) | Amount       | Total cost ($) |
|-----------|---------------|--------------|----------------|
| Electricity | $0.058 kWh⁻¹ | 85-86.40 kWh | 4.90-5.00      |

Total surface modification cost ($)

| Modifying agent | Incorporation | (1) Ni(NO₃)₂·6H₂O | (2) NH₄VO₃ | (3) Fe(NO₃)₃·9H₂O | (4) Ce(NO₃)₃·6H₂O |
|-----------------|---------------|-------------------|-----------|--------------------|--------------------|
| Activated carbon (AC) | (1) CO₂-AC | 57.10-556.50 | 57.30-556.70 | 57.00-556.40 | 57.80-557.20 |
|                  | (2) Steam-AC | 147.80-764.90 | 148.00-765.10 | 147.70-764.80 | 148.50-765.50 |
|                  | (3) H₃PO₄-AC | 21.50-21.90 | 21.70-22.10 | 21.40-21.80 | 22.10-22.60 |
|                  | (4) H₂SO₄-AC | 16.10-16.50 | 16.30-16.70 | 16.00-16.50 | 16.70-17.20 |
|                  | (5) ZnCl₂-AC | 14.70-15.30 | 14.90-15.50 | 14.60-15.20 | 15.40-16.00 |
|                  | (6) KOH-AC | 11.80-17.30 | 12.00-17.50 | 11.70-17.20 | 12.50-17.90 |
|                  | (7) K₂CO₃-AC | 12.00-12.60 | 12.20-12.80 | | 11.90-12.50* | 12.70-13.30 |
|                  | (8) NaOH-AC | 12.80-25.30 | 13.00-25.50 | 12.70-25.20 | 13.50-26.00 |
|                  | (9) H₃PO₄, CO₂-AC | 73.20-133.20 | 73.40-133.40 | 73.20-133.10 | 73.90-133.90 |
|                  | (10) H₂SO₄, CO₂-AC | 67.70-126.70 | 67.90-126.90 | 67.60-126.60 | 68.40-127.30 |
|                  | (11) ZnCl₂, CO₂-AC | 66.60-126.60 | 66.80-126.80 | 66.60-126.50 | 67.30-127.30 |
|                  | (12) KOH, CO₂-AC | 63.60-127.70 | 63.80-127.90 | 63.50-127.70 | 64.20-128.40 |
|                  | (13) NaOH, CO₂-AC | 64.70-135.90 | 64.90-136.10 | 64.60-135.80 | 65.40-136.50 |
Table 7 (continued).

| Incorporation | Modifying agent | Amount | Total cost ($) |
|---------------|-----------------|--------|----------------|
| AC            | (5) BaO         | 63.20-562.60 | 63.50-562.90 |
| (1) CO₂-AC    | (6) MgO         | 105.00-604.40 | 105.00-604.40 |
| (2) Steam-AC  | (7) CuO         | 186.90-804.00 | 186.90-804.00 |
| (3) H₃PO₄-AC  | (8) TiO₂        | 60.60-61.00   | 60.60-61.00   |
| (4) H₂SO₄-AC  | (9) CeO₂        | 55.20-55.60   | 55.20-55.60   |
| (5) ZnCl₂-AC  | (10) H₂SO₄, CO₂-AC | 53.80-54.40 | 53.80-54.40 |
| (6) KOH-AC    |                 | 50.90-56.40   | 50.90-56.40   |
| (7) K₂CO₃-AC  |                 | 51.10-51.70   | 51.10-51.70   |
| (8) NaOH-AC   |                 | 51.90-64.40   | 51.90-64.40   |
| (9) H₃PO₄, CO₂-AC |                 | 112.30-172.30 | 112.30-172.30 |
| (10) H₂SO₄, CO₂-AC |             | 106.80-165.80 | 106.80-165.80 |
| (11) ZnCl₂, CO₂-AC |             | 105.70-165.70 | 105.70-165.70 |
| (12) KOH, CO₂-AC |             | 102.70-166.80 | 102.70-166.80 |
| (13) NaOH, CO₂-AC |             | 103.80-175.00 | 103.80-175.00 |

| Utility | Unit cost ($) | Amount | Total cost ($) |
|---------|---------------|--------|----------------|
| Electricity | $0.058 kWh⁻¹ | 85-86.40 kWh | 4.90-5.00 |

a Value in **bold** indicates minimum value for surface modification of AC cost.
3.2. Selection of least expensive AC production process

A comparison of the minimum estimated production cost from physical, chemical and physiochemical activation and amine and metal post-activation surface modification process for 100 g AC production is summarized in table 8. Based on table 8, oil palm-based ACs produced from various activation and surface modification approaches minimum estimated cost can be rank as below:

Minimum production/modification cost: KOH activation (chemical activation) < Fe(NO₃)₃·9H₂O functionalization (metal surface modification of AC) < DEA functionalization (amine surface modification of AC) < Physiochemical activation by ZnCl₂ and CO₂ < CO₂ activation

CO₂ activation with 99.80% CO₂ and the multi-sequences physiochemical activation by ZnCl₂ and 99.80% CO₂ estimated respectively 86-97% and 87-88% higher production cost than KOH activation. For post-activation surface modification method, the K₂CO₃ activation with added respective DEA and Fe(NO₃)₃·9H₂O functionalization have 48-51% and 54-63% higher estimated modification cost than the sole KOH activation, while 71-94% and 77-95% lower than the CO₂ activation. The main factor which causes the high production cost for CO₂ activation is the high CO₂ amount used for prolonged duration of activation process.

Overall, chemical activation with KOH is the least expensive method among the activation and surface modification methods, in producing the same yield of oil palm-based ACs with the lowest estimated production cost.

Table 8. Comparison of activation/post-activation surface modification process towards AC production with minimum estimated production cost.

| Types of process                                              | Estimated production/modification cost ($) | Estimated product cost ($) | Cost Rank |
|---------------------------------------------------------------|------------------------------------------|----------------------------|-----------|
| Physical activation: CO₂ activation with 99.80% CO₂          | 51.70-258.50                             | 0.52-2.59                  | Highest   |
| Physiochemical activation: ZnCl₂ and 99.80% CO₂              | 62.40-64.50                              | 0.62-0.65                  |           |
| Amine surface modification of AC: DEA functionalization of K₂CO₃-activated oil palm carbon in CH₃OH | 14.90-15.70                             | 0.15-0.16                  |           |
| Metal surface modification of AC: Fe(NO₃)₃·9H₂O functionalization of K₂CO₃-activated oil palm carbon | 11.90-12.50                             | 0.12-0.13                  |           |
| Chemical activation: KOH with ≥ 85% purity KOH pellets       | 7.30-8.10                                | 0.073-0.081                | Lowest    |
4. Conclusion
A laboratory scale cost estimation of AC production was developed for five activation (i.e., physical, chemical and physiochemical activation) and post-activation surface modification (i.e., amine and metal functionalization) methods. A comparative assessment on the production/modification costs of these activation/modification methods are studied to identify and select a cost-friendly method with the lowest production cost. The production cost is estimated based on the purchased chemical prices and the utility costs quoted from the combination of vendors and official industrial tariffs. Of the five methods investigated for the production cost evaluation, chemical activation with KOH has quoted the lowest production cost with minimum estimated production cost of $0.073 g⁻¹, while PEI functionalization of steam-activated oil palm carbon presented the highest modification cost of up to $8.73 g⁻¹. High purchased chemical prices for the steam-activated oil palm carbon and high utility cost due to prolonged process operation are the significant factors that cause the highest estimated modification cost for PEI functionalization. Nonetheless, the estimation of this laboratory scale production cost analysis cannot be considered a promising baseline for potential scaling up to estimate the pilot scale production cost, due to lack of estimation for the purchased equipment cost, capital cost, fixed capital investment cost, and annual operating costs for labor, supplies and general works required for production. Therefore, future studies could include any laboratory capital and operating expenditures associated with the purchase, building, construction, installation, and the operation services required in the production to demonstrate a small pilot scale production cost estimation.

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