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Research article

Performance, life cycle assessment, and economic comparison between date palm waste biochar and activated carbon derived from woody biomass

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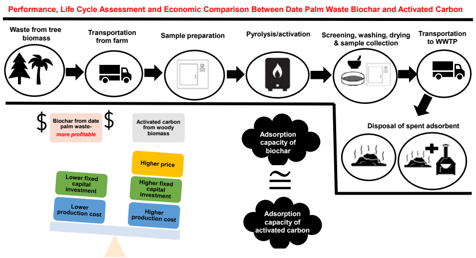
HIGHLIGHTS

- Biochar GWP was 2.36 kg CO_2eq/kg and activated carbon GWP was 8.34 kg CO_2eq/kg.
- Biochar CED was 20.3 MJ/kg and activated carbon CED was 119.5 MJ/kg.
- Adsorption capacities of biochar were comparable with activated carbon.
- Production cost of biochar was $1.06/kg and activated carbon was $1.34/kg.
- Sensitivity analysis showed that switching solar energy reduced CED and GWP.

GRAPHICAL ABSTRACT



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ABSTRACT

Currently, comparisons between biochar and activated carbon in terms of performance, environmental impacts as well as financial implications are limited. In this study, biochar sourced from date palm waste were analysed using gate-to-grave life cycle assessment approach and results were compared to activated carbon derived from woody biomass. Simapro 8.5 software was used to quantitatively simulate the environmental impacts of both adsorbents. Date palm waste biochar and activated carbon global warming potentials (GWPs) were found to be 1.53 and 8.96 kg CO_{2eq}/kg respectively. The cumulative energy demand (CED) for producing date palm waste biochar was found to be 20.3 MJ/kg, whereas, activated carbon resulted in 119.5 MJ/kg. Both adsorbents' performance in terms of adsorption capacity were compared, and it was found that biochar is comparable with activated carbon. The economic performance demonstrated that the average cost of production of date palm waste biochar and activated carbon were $1.06/kg and $1.34/kg, respectively. Sensitivity analysis showed that when the source of energy was changed to renewable energy, a CED dropped to 105.2 MJ/kg and 7.68 MJ/kg, a GWP dropped to 7.29 kg CO_2 eq. and 0.665 kg CO_2 eq. and production costs dropped to $1.30 and to $1.04 for producing activated carbon and biochar respectively. Based on the results of the study, date palm waste biochar is more cost-effective, shows less environmental impact, and has comparable adsorption efficiency as compared to activated carbon.

1. Introduction

Annually, the world generates approximately 2 billion tons of municipal solid waste (MSW), and by 2050 it is expected to grow to 3.40 billion tons which will lead to implications on the environment, health, and prosperity (Kaza et al., 2018). Yard waste/garden waste/agricultural waste contributes 10–15% of the total generated municipal waste (SCAD, 2020; USEPA, 2021). Annually, the production of agricultural waste globally is around 1 billion tons (Agamuthu, 2009). According to a study, forestry, agricultural waste and MSW biomass contribute about 13% to

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the overall greenhouse gas emissions (GHG) in Canada (Dahal et al., 2018). Therefore, sustainable waste management is necessary. Biomass sources possess the highest potential for economic profitability (+\$69 t^{-1} dry feedstock when CO_2e emission reductions are valued at \$80 t^{-1} CO_2e) (Roberts et al., 2010). In terms of agricultural/yard waste, waste from date palm trees in particular is abundant in the Gulf Cooperation Council Countries; 50 kt of date palm waste are generated which end up in disposal sites in the United Arab Emirates (UAE) alone (Sizirici et al., 2021). Similarly, waste from 22 million date palm trees ends up being disposed in landfills or burned in open fields in the Kingdom of Saudi Arabia (Usman et al., 2015). Recently, production of biochar from waste materials such as tree residues and biomass from agricultural and animal waste has gained popularity in order to create a sustainable solution to the waste management problem (Liu et al., 2022). Biochar is a solid, carbon-rich product formed when biomass is pyrolyzed in oxygen deficient conditions. it is used in a number of areas such as heat and power production, carbon sequestration, soil amendment, fertilizer, and adsorbent for water/wastewater treatment (Amin et al., 2016). Biochar is found to be advantageous in adsorbing and removing pollutants from aqueous solutions due to its favourable characteristics such as its mineral-rich, well-developed porous structure, high specific surface area, abundance of functional groups which are all influenced by the feedstock type and conditions of pyrolysis such as temperature, residence time and heating rate (Qiu et al., 2022). For instance, biochar derived from plant biomass particularly have the tendency to form more porous structures due to the presence of cellulose and lignin which can be influential in the adsorption of contaminants via pore filling (Liang et al., 2021). Moreover, they are rich in carbon and oxygen elements which leads to the formation of oxygenated functional groups which play major roles in the removal of contaminants via surface complexation (Fseha et al., 2021; Liang et al., 2021).

The utilization of plant biomass derived biochar as an adsorbent to remove inorganic and organic pollutants from aqueous solutions has been demonstrated in several studies. For instance, Fseha et al. (2022) found that date palm biochar pyrolyzed at 500 °C showed 3.57 mg/g of manganese, and 4.18 mg/g of nitrate adsorption capacities in mixed aqueous solutions. Additionally, date palm biochar pyrolyzed at 500 °C displayed adsorption capacities of 49.76 mg/g and 26.90 mg/g for ammonium and phosphate ions in single solution respectively (Fseha et al., 2021). Similarly, Pellera et al. (2012) observed that rice husks, olive pomace and orange waste biochar pyrolyzed at 300 °C adsorbed 2.87 mg/g, 1.29 mg/g and 1.38 mg/g of copper respectively. Chen et al. (2011) found that corn straw derived biochar pyrolyzed at 600 °C showed 12.5 mg/g of copper and 11 mg/g of zinc adsorption capacities. Zhang et al. (2018) reported that Chinese herb residue derived biochar pyrolyzed at 600 °C yielded 9.7 mg/g of phenol adsorption capacity. Yoon et al. (2021) used grape pomace derived biochar pyrolyzed at 350 °C and found that adsorption capacity for a pesticide (cymoxanil) was 161 mg/g.

Globally, 1500 km^3 of wastewater is produced annually, and hence there exists a strong incentive to develop cost-effective and environmentally friendly techniques for treating contaminated waters due to the increasingly stringent environmental regulations as well the growing interest in safe reuse (Ahmaruzzaman, 2011; Qu et al., 2013; UNESCO, 2003). Biochar can meet this expectation since it uses waste materials as feedstock, and it has abundant functional groups, high porosity and surface area which lead to the effective removal of pollutants (Shafiq et al., 2018). However, activated carbon is still the most adopted commercial adsorbent in treatment plants (Wang et al., 2008). The production and regeneration of activated carbon has been proven to be costly, which limits its use in large scale treatment (Mahdi et al., 2018).

Currently, comparisons between biochar and activated carbon in terms of performance, environmental impacts, and financial implications are limited. Life Cycle Assessment (LCA) with impact assessment determines the environmental impact of new products/technologies towards the environment and ecosystem (Cerdas et al., 2017; Cossutta et al., 2020; Igos et al., 2020). There are several LCA studies focusing on environmental aspect of producing biochar. Hamedani et al. (2019) used two different feedstocks (willow and pig manure) for biochar production and observed that biochar derived from willow achieved better LCA results than biochar derived from pig manure. Brassard et al. (2018) reported that higher pyrolysis temperature results in higher GHG emissions due to higher energy requirements. Homagain et al. (2015) observed that biochar land application consumes more energy than conventional systems, however it reduces GHG emissions and improves ecosystem quality. Studies concluded that feedstock, type of pyrolysis, and pyrolysis temperature impact LCA results of biochar production. The other studies focused on LCA of activated carbon production. Loya-González et al. (2019) found that the impregnation with KOH and higher pyrolysis temperatures were main contributors to higher environmental damage of corn pericarp derived activated carbon production. Gu et al. (2018) found that GHG emissions from woody biomass derived activated carbon (8.6 kg CO_2 eq.) were less than half of that of coal derived activated carbon (18.28 kg CO_2 eq.). These studies revealed that different feedstock, impregnation techniques, and pyrolysis temperature affect LCA results. LCA studies for both biochar and activated carbon production revealed that fossil fuel usage contributed about 70% of the overall process towards impacted environmental categories (Ji et al., 2018; Tiegam et al., 2021).

Cost-benefit analyses based on revenue earned or drop in the costs for biochar production as compared to activated carbon production will help end users to compare the production cost which is a key factor in leading the bio-economy its marketing and application (Ji et al., 2018; Nematian et al., 2021). The operational expenses from the unit processes need to be covered to ensure that the product is economically viable (Ahmed et al., 2016). The economical aspect of biochar has been studied in various techno-economic studies. For instance, Huang et al. (2015) found that it is economically feasible to use poultry litter to produce biochar as long as the heat/power was utilized in the processes of pyrolysis and gasification. In another study, making use of forest residue was investigated; the minimum selling price of biochar derived from forest residue with the utilization of portable systems, was estimated to be \$1.04 kg^{-1} (Sahoo et al., 2019). Alhashimi and Aktas (2017) compared the cost of biochar and activated carbon and reported that granular and powdered activated carbon costs were \$6.40 kg^{-1} and \$1.20–2.00 kg^{-1} respectively, whereas biochar costs were \$0.8–1.5 kg^{-1}. Another study reported \$1.6 kg^{-1} sales price for biochar (Nematian et al., 2021).

Ultimately, performance evaluations for removal of pollutants by date palm biochar and activated carbon will contribute to an effective comparison of biochar's adsorption and removal capacity against the commercial products. Biochar has been studied to remove inorganic and

Table 1. Life Cycle Inventory for date palm biochar (actual operation data) and woody biomass activated carbon.

Material input (biochar production)	Amount
Date palm leaf and frond waste	2.0 kg
Drying	1.40 kWh
Pyrolysis	0.076 kWh
Sieving, crushing, and washing	0.093 kWh
Material output	-
Biochar	1.00 kg
Material input (Activated carbon)	**Amount** (Gu et al., 2018)
Woody biomass	2.20 kg
Natural gas	2.33 m^3
Liquid nitrogen	0.15 kg
Water (for washing and dilution)	2.11 kg
Power (drying and shaking)	1.65 kWh
Power (pyrolysis)	0.076 kWh
Material output	-
Activated carbon	1.00 kg

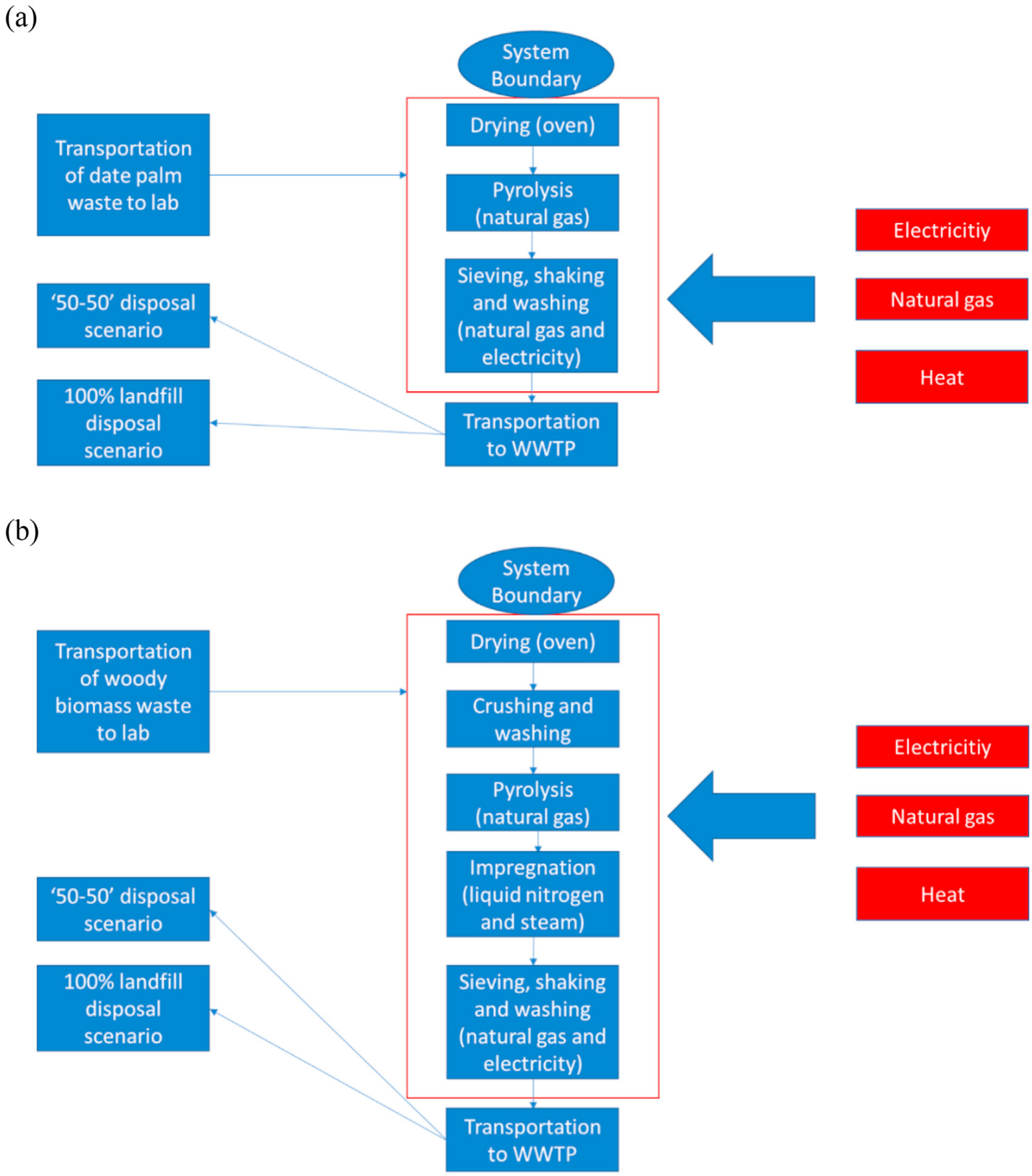

Figure 1. System boundary for (a) biochar (b) activated carbon.

organic pollutants from aqueous solutions, and it was reported that its adsorption capacity is comparable to activated carbon. For instance, nickel adsorption capacity by almond shell derived biochar was 22.22 mg/g as reported by Kılıç et al. (2013), and by almond husk derived activated carbon was 4.89 mg/g according to Hasar (2003). Wahid et al. (2022) reported phenol adsorption capacity by activated carbon derived from waste coconut shells to be 0.027 mg/g, and that by biochar derived from pine fruit shells to be 26.74 mg/g according to Mohammed et al. (2018).

In this study, the biochar was derived from date palm waste due to its abundance in UAE. It is important to utilize the abundant waste present in a certain location to produce adsorbents that can be utilized in wastewater treatment plants (WWTPs) in that region. An LCA comparison (from production until disposal) between biochar derived from date palm waste and activated carbon derived from woody biomass (LCA of activated carbon was constructed based on woody biomass to activated carbon production process information found in literature) was conducted. Several disposal scenarios such as incineration and landfilling were discussed after the exhaustion of both adsorbents used in the treatment plants. Impact categories such as GHG emissions, ozone formation, and marine eutrophication were observed in this comparison. A cost analysis was conducted for biochar and activated carbon and results were compared to understand the economic benefits of implementing biochar as an adsorbent to treat wastewater in WWTPs. Additionally, a sensitivity analysis for biochar and activated carbon production was conducted to determine the degree of environmental impact factors and cost dependence on various processes such as transportation and energy source utilized. Lastly, adsorption capacity performance of date palm biochar and activated carbon were evaluated against a variety of pollutants in aqueous solutions. The outcomes from this study is expected to provide a comprehensive perspective on the biochar as a low-cost, environmentally friendly, and efficient adsorbent as an alternative to activated carbon.

2. Materials and methods

2.1. Life cycle inventory for biochar and activated carbon production

Date palm frond and leaves waste were dried under the sun and chopped to 0.5 cm length and dried in an oven for 24 h at 105 °C.

Table 2. Summary of LCA results.

Impact category	Unit	100% landfilling AC	'50-50' AC disposal	100% landfilling BC	'50-50' BC disposal
Global warming potential	kg CO2 eq	8.33	8.96	**1.53**	1.91
Stratospheric ozone depletion	kg CFC-11 eq	8.68E-07	8.41E-07	**8.40E-07**	1.59E-06
Ionizing radiation	kBq Co-60 eq	6.91E-02	7.29E-02	**4.88E-02**	4.74E-02
Ozone formation, Human health	kg NOx eq	1.18E-01	1.18E-01	**4.84E-03**	5.05E-03
Fine particulate matter formation	kg PM2.5 eq	1.14E-03	**1.12E-03**	1.16E-03	1.18E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.88E-01	1.88E-01	**4.93E-03**	5.15E-03
Terrestrial acidification	kg SO$_2$ eq	3.01E-03	3.00E-03	**2.99E-03**	3.05E-03
Freshwater eutrophication	kg P eq	1.38E-04	1.32E-04	**1.17E-04**	1.41E-04
Marine eutrophication	kg N eq	5.21E-04	5.27E-04	**1.03E-03**	5.30E-04
Terrestrial ecotoxicity	kg 1,4-DCB	1.99	**1.98**	2.11	2.39
Freshwater ecotoxicity	kg 1,4-DCB	**4.51E-01**	**4.51E-01**	8.83E-01	7.17E-01
Human carcinogenic toxicity	kg 1,4-DCB	2.50	**1.50**	3.10	4.40
Land use	m2a crop eq	1.87E-02	1.89E-02	1.64E-02	**1.44E-02**
Mineral resource scarcity	kg Cu eq	**1.43E-03**	1.50E-03	1.51E-03	1.70E-03
Fossil resource scarcity	kg oil eq	2.56	2.57	0.51	**0.50**
Water consumption	m3	7.35E-03	1.35E-01	**2.12E-03**	2.96E-03
Cumulative Energy Demand (CED)	MJ/kg	119.50		**20.33**	

AC: Activated Carbon, BC: Biochar and bold numbers show the lowest values for each impact categories.

Subsequently, they were placed in stainless-steel containers covered with aluminum foil to prevent air intrusion and pyrolyzed in a muffle furnace (Luoyang Hongda Furnace Muffle Furnace: 0.77 m^3 capacity, 1800 W of heater wattageat 500 °C at a rate of 8 °C/min temperature increment, totaling 5.04 h of residence time) to produce biochar (Alibaba, 2022). No inert gas was utilized during pyrolysis process. After pyrolysis was completed, the biochar samples were allowed to cool for 3–4 h inside the furnace. Then, biochar was grinded, and sieved to 0.15 mm in size, washed with deionized water, dried at 105 °C in an oven for 2 h, and kept in airtight containers. The detailed chemical and physical characterizations of date palm biochar were reported in a previous study (Sizirici et al., 2021). It was deduced that 2 kg of dried biomass yielded 1 kg of biochar. All material and energy inputs observed during the preparation of date palm biochar were used to construct the life cycle inventory (LCI) as shown in Table 1.

Production process, material and energy inputs for woody biomass activated carbon were adopted from (Gu et al., 2018) and used to prepare LCI as shown in Table 1. The adopted study used timber as biomass feedstock. The timber logs were cut, crushed, and sieved into microchips with dimensions up to 13 mm. The study used 3 min residence time at 1000 °C pyrolysis temperature and 550 °C super-heated steam at 816 °C, 927 °C at the carbonization and activation process steps, respectively. The carbonization was conducted using a specific renewable natural gas (RNG) system. Nitrogen purging was conducted at a rate of around 2.90 m^3/s. The adopted study observed that 2.2 kg of biomass would be required to produce 1 kg of activated carbon. Unification of the production process of both adsorbent, same muffle furnace energy inputs were used for LCA (Luoyang Hongda Furnace) (Alibaba, 2022).

2.2. *Life cycle assessment*

SimaPro 8.5 software with 'Recipe Endpoint' weighing method was used for the gate to grave LCA for production of 1 kg of activated carbon from woody biomass and 1 kg of biochar from date palm waste. The environmental impacts (global warming potential, stratospheric ozone depletion, ionizing radiation, ozone formation, human health and terrestrial ecosystem, terrestrial acidification, freshwater and marine eutrophication, freshwater eco-toxicity, human carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity and water consumption) as well as cumulative energy demand (CED) are quantified for date palm waste based biochar and woody biomass based activated carbon life cycles. The system boundaries and the overall processes considered in producing the biochar and activated carbon up until its usage in the WWTP and in final disposal are shown in Figure 1(a) and (b). LCA for production of biochar and activated carbon began with collecting the date palm waste and woody biomass from specified farms in Abu Dhabi. Transportation of date palm waste from a nearby date farm to Khalifa University (KU) (54.6 km) as well as transportation of woody waste from another farm to KU (42.7 km) were considered. Production of biochar followed drying, pyrolysis, sieving and washing. Activated carbon production followed drying, crushing, pyrolysis, and steam activation.

The transportation distance of produced date palm waste biochar and activated carbon from KU to the WWTP was recorded to be 39.1 km. Lastly, two disposal scenarios were analyzed for exhausted adsorbents assuming that biochar and activated carbon were used in treatment process at WWTP. The first scenario includes a 100% landfill disposal process in which 100% of exhausted adsorbents is transported from WWTP to landfill located 46 km from the WWTP. The second scenario requires 50-50 disposal process in which 50% of the exhausted adsorbents is transported from WWTP to the incinerator located 40 km from WWTP, and the remaining 50% of the exhausted adsorbents is transported to the landfill. The contributions of each production process including drying, pyrolysis, transportation, and disposal to the environmental impacts categories in terms of global warming potential, stratospheric ozone depletion, and ionizing radiation were analyzed as well.

Lastly, a sensitivity analysis was conducted for producing activated carbon and biochar. Two variables were changed to observe the effects on the environmental impact factors as well as the cost; the distances covered transporting the waste (for both adsorbents) to the lab as well as activated carbon and biochar to the WWTP, and the source of energy used for heating and electricity in the production of activated carbon and biochar. The distances were reduced by a factor of approximately four whilst the energy source was varied from natural gas to solar energy produced from photovoltaic panels in a solar farm. The price of electricity from photovoltaic panels was retrieved from literature and was found to be 1.35 US'/kWh in the UAE (IRENA, 2021). The results were compared to determine which varying factor resulted in a higher change of results.

2.3. *Economic assessment*

For the economic assessment, expenses from the unit processes need to be covered to ensure that the product is viable (Ahmed et al., 2016). Economic assessment in this study was conducted based on the commercial scale production scenario for both adsorbents. The unit processes involved to produce biochar are: sample preparation, pyrolysis, screening, sample collection and transportation of the material for the

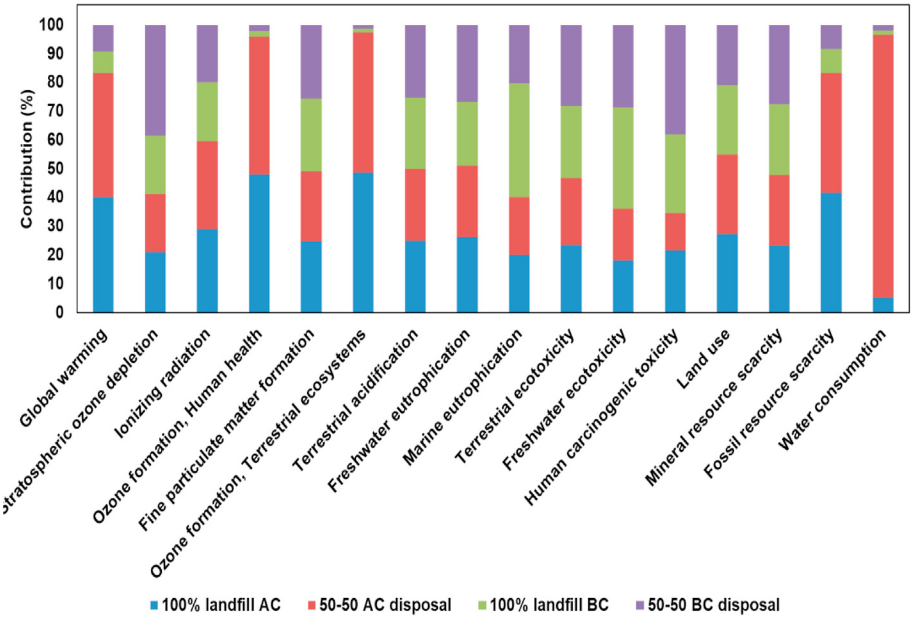

Figure 2. Contribution (%) on each impact category of '50-50' disposal scenario for biochar and activated carbon and 100% landfilling scenario for biochar and activated carbon.

final use in WWTP. The unit operations involved in woody biomass derived activated carbon production are sample preparation, pyrolysis, activation, screening, sample collection and transportation of the adsorbent to WWTP. Currently, it is difficult to get comprehensive information on prices and cost for biochar production (Ahmed et al., 2016). Hence, the cost was estimated from literature data taking into consideration the various unit processes. For instance, for activated carbon production (900 kg per day) based on an initial feed of 2000 kg per day of woody biomass, the annual cost of raw materials including chemicals used for activation ($7000) was estimated from a literature study (Lai and Ngu, 2020).

The net profits of date palm biochar and activated carbon production systems that were based on the functional unit of 1 dry kg of the dry biomass waste are calculated from Eq. (1) and Eq. (2), respectively (Roberts et al., 2010):

$$P = BC + Tip + Avo - F - Trans - OC - FCI \quad (1)$$

$$P = AC + Tip + Avo - F - Trans - OC - FCI \quad (2)$$

Where P is the profit that is associated with 1 dry kg of date palm biochar or 1 dry kg of activated carbon, BC and AC are the revenue derived from selling the biochar and activated carbon, respectively. Tip is the value that was received from any tipping or disposal obtained of the feedstock. Avo is the value received from the avoided cost of composting, F is the collection cost of the feedstock, Trans is the cost incurred from transporting both the feedstock from the farms to KU and the product (biochar or activated carbon) from KU to the WWTP, FCI is the fixed capital investment for processing a single unit of the feedstock, and OC is the unit operating cost associated with the processing feedstock.

Per functional unit (kg), the total cost of transportation is the summation of the feedstock and biochar/activated carbon transportation costs (Roberts et al., 2010):

$$Trans = Trans(F) + Trans\ (BC\ or\ AC) \quad (3)$$

$$Trans\ (F\ or\ BC\ or\ AC) = (4.1 + 0.08 * D)/1000 \quad (4)$$

whereby,

D is the distance in km, 54.6 km and 42.7 km for the biochar and activated carbon feedstock transportation, respectively. While 39.1 km is the distance for biochar or activated carbon transportation from production point to WWTP. $4.10 is the loading and unloading charge per tonne, and $0.08 is the shipping cost per t-km (Roberts et al., 2010). As for the tipping fee, depending on from where the yard waste is sourced, the collection can be a source of revenue for the waste management. Hence, the feedstock collection cost (F) is considered negligible for the cases of both biochar and activated carbon as they are both sourced from waste biomass. For the purpose of this analysis, for both cases of biochar and activated carbon, a conservative estimate of $27 per ton or $0.02 per kg was used for the tipping fee, and $10.81 per ton or $ 0.01 per kg for the avoided cost of compost (Roberts et al., 2010).

The estimated product cost (F) can be obtained by Eq. (5) (Lai and Ngu, 2020):

$$F = O/e \quad (5)$$

Whereby O is the total operating cost calculated by the summation of direct production costs including utilities and payroll costs, fixed charges which includes depreciation and insurance costs, overhead costs i.e., costs for the general upkeep of the site, and general expenses. The cost of electricity per kWh ($0.0408) and the salary of the operators were obtained from a study based in the UAE (Ashraf et al., 2017). e is the annual production capacity in a 320-days year. For steam-activated activated carbon, the final possible yield was estimated to be 45% or about 900 kg/day, based on a feed of 2000 kg/day and assuming a 320-days year and three shifts in a 24 h day. As for biochar, the final yield was estimated as 50% or 1000 kg/day, based on a feed of 2000 kg/day and assuming a 320-days year and three shifts in a 24 h day.

The net present value (NPV) was evaluated to propose investment in the facility which is as follows:

$$NPV = (r * O) + C \quad (6)$$

Whereby r is the discount rate which was considered to be 20% in this case, and C is the total annual fixed capital investment obtained from the summation of the direct/indirect manufacturing cost and the total equipment cost (Lai and Ngu, 2020).

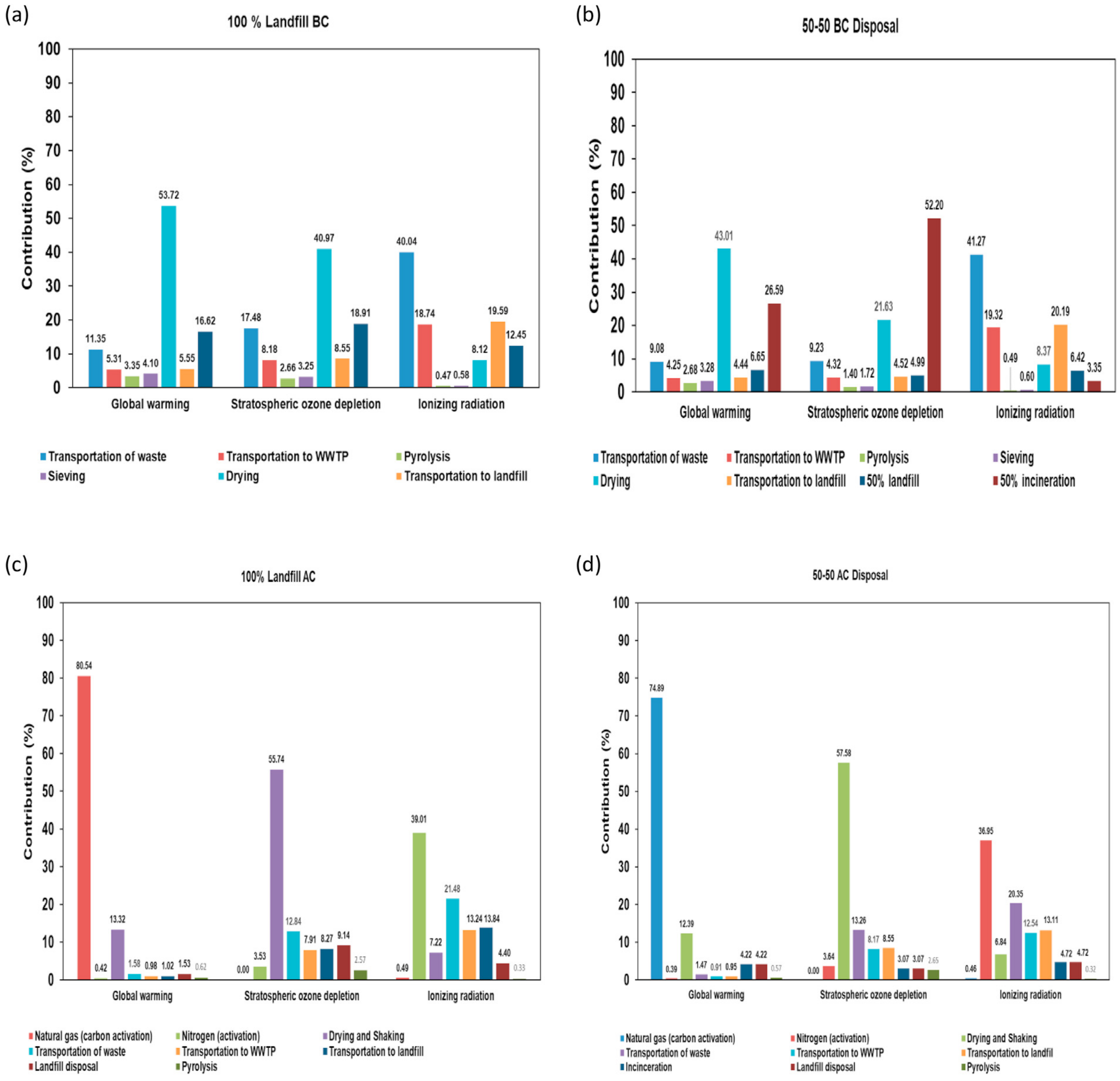

Figure 3. LCA contribution analysis, (a): 100% landfill BC, (b): '50-50- BC AC, (c): 100% landfill disposal, (d) '50-50′ AC.

2.4. Performance assessment

For the performance assessment between biochar and activated carbon in terms of adsorption of inorganic and organic pollutants, comprehensive literature review was conducted using Scopus database considering journal papers published between 2004 to 2022. The key terms “biochar adsorption inorganics” and “biochar adsorption organics” yielded 474 and 1994 journal papers results, respectively. As for activated carbon, the key terms “activated carbon adsorption inorganics” and “activated carbon adsorption organics” gave 1026 and 7184 journal papers results, respectively. Out of all these articles, 34 articles including those from our previous investigations using date palm waste derived biochar to remove inorganics were selected for assessment. As a means of comparison of performance, adsorption capacity was used which is defined as the quantity of adsorbate molecules taken up by a particular adsorbent per unit mass of the adsorbent as shown in Eq. (7) (Sizirici et al., 2021).

$$qe = (C_0 - C_e) \bullet \frac{V}{m} \tag{7}$$

where, qe = adsorption capacity (mg/g), C_0 = initial concentration (mg/L), C_e = final concentration (mg/L), V = volume of the sample (L) and m = mass of the adsorbent (g).

Accordingly, adsorption capacities of date palm biochar and other biochars derived from different raw materials and different types of activated carbon against a variety of pollutants that are commonly found in wastewater (Cu^{2+}, Fe^{2+}, Ni^{2+}, Zn^{2+}, Mn^{2+}, Cd^{2+}, Cr^{6+}, Pb^{2+}, NH_4^+, NO_3^-, PO_4^{3-}, sulfamethoxazole, atenolol, ibuprofen and phenol) were evaluated using the literature for effective comparison of performance.

3. Results and discussion

3.1. LCA results

The environmental impacts of activated carbon in both 50-50% and 100% landfilling disposal scenarios were higher in 14 impact categories out of 16 than biochar in both scenarios as shown in Table 2 and Figure 2. On the other hand, 100% landfilling disposal scenario of the biochar showed the lowest environmental impact in 9 categories.

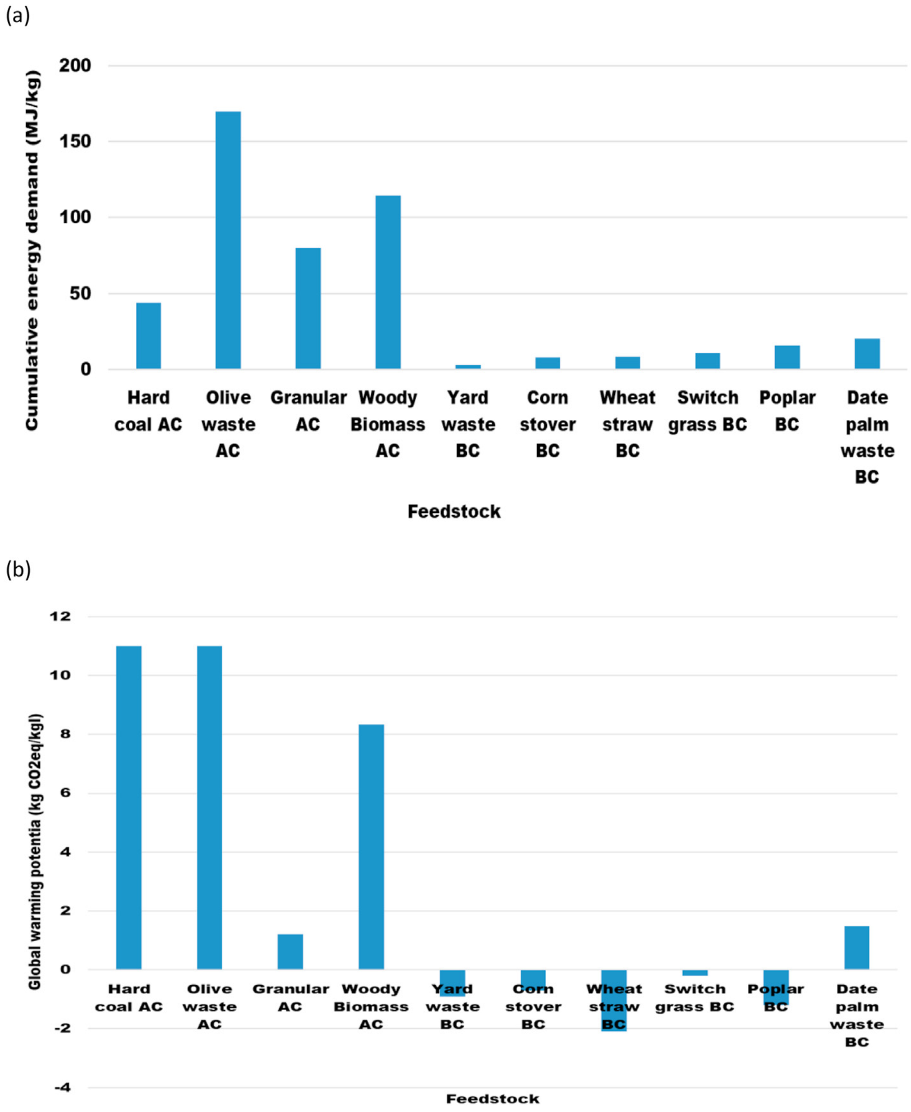

Figure 4. Literature comparison of a) Cumulative Energy Demand and b) Global warming potential between biochar and activated carbon (Alhashimi and Aktas, 2017).

Global warming potential, stratospheric ozone depletion, and ionizing radiation were selected as categories to analyze the impact of each production process including drying, pyrolysis, transportation, and disposal on the environment during the life cycles of activated carbon and biochar as shown in Figure 3a-d. Drying due to electricity consumption, and landfill disposal represented the highest contributors in the impact categories for the scenario for 100% landfill disposal of biochar. In this scenario, drying was dominant process for global warming and stratospheric ozone depletion categories contributing approximately 53% and 40%, respectively. The transportation of waste process was the highest contributor in the ionizing radiation (40%) due to the emission of ozone depleting gases such as CFCs and methane gases as shown in Figure 3 (a). Among the highest contributors towards the three impact categories, drying accounts for 43% for global warming due to electricity consumption, incineration accounts for 52% for stratospheric ozone depletion, and transportation of waste accounts for 40% for ionizing radiation at '50-50' disposal of biochar scenario as displayed in Figure 3 (b). The carbon activation due to electricity and nitrogen consumption and drying and shaking processes due to electricity consumption are the highest contributors in the global warming category for the 100% landfill disposal scenario of activated carbon. Additionally, the usage of liquid nitrogen was the dominant contributor to the ionizing radiation, drying and shaking process were the lead contributors in the stratospheric ozone depletion as shown Figure 3 (c). Another study also reported that the impregnation (activation) was the largest contributing factor in several LCA impact categories during production of activated carbon from corn pericarp feedstock (Loya-González et al., 2019). In another study, electricity usage was found to be the largest contributor to impact categories during production of activated carbon from cocoa pods (Tiegam et al., 2021). Similarly, carbon activation and pyrolysis processes gave the highest contributions in all the impact categories for '50-50' disposal scenario of activated carbon as shown Figure 3 (d).

LCA results for both adsorbents in terms of cumulative energy demand and global warming potential (GWP) were compared with the literature. It was found that date palm biochar energy demand was 20.33 MJ/kg which is less than 119.5 MJ/kg for woody mass activated carbon production and other activated carbons derived from different feedstock as shown in Figure 4(a). In addition, date palm biochar GWP was 1.53 kg CO_{2eq}/kg which was less than 8.96 kg CO_{2eq}/kg for woody mass activated carbon and other activated carbons derived from different feedstock as shown in Figure 4(b). However, our GWP result for date palm biochar was higher than reported values in a study in which biochar was used for soil amendment or carbon sequestration purposes (Alhashimi and Aktas, 2017). Soil amendment or carbon sequestration lower CO_2

Table 3. Sensitivity analysis summary comparison.

Impact category	Unit	Original 100% landfill AC scenario	'Reduced distance' 100% AC landfilling scenario	'Solar energy source'100% AC landfilling scenario	Original 100% landfilling BC Scenario	'Reduced distance' 100% BC landfilling scenario	'Solar energy source' 100% BC landfilling scenario
Global warming potential	kg CO2 eq.	8.33	8.23	**7.29**	1.53	1.29	**0.665**
Stratospheric ozone depletion	kg CFC11 eq.	8.68E-07	7.72E-07	**4.28E-07**	8.40E-07	6.35E-07	**4.62E-07**
Ionizing radiation	kBq Co-60 eq.	6.91E-02	**5.47E-02**	7.51E-02	4.88E-02	**2.04E-02**	4.53E-02
Ozone formation, Human health	kg NOx eq.	0.118	0.118	**0.116**	4.84E-03	3.71E-03	**1.87E-03**
Fine particulate matter formation	kg PM2.5 eq.	1.14E-03	9.45E-04	**9.23E-04**	1.16E-03	**7.62E-04**	7.68E-04
Ozone formation, Terrestrial ecosystems	kg Nox eq.	0.188	0.187	**0.185**	4.93E-03	3.76E-03	**1.93E-03**
Terrestrial acidification	kg SO2 eq.	3.01E-03	2.60E-03	**2.00E-03**	2.99E-03	2.13E-03	**1.68E-03**
Freshwater eutrophication	kg P eq.	1.38E-04	**1.12E-04**	2.14E-04	1.17E-04	**6.48E-05**	1.18E-04
Marine eutrophication	kg N eq.	5.21E-04	**5.20E-04**	5.30E-04	1.03E-03	**1.03E-03**	**1.03E-03**
Terrestrial ecotoxicity	kg 1,4-DCB	1.99	**1.50**	6.30	2.11	**0.821**	2.26
Freshwater ecotoxicity	kg 1,4-DCB	0.451	**0.445**	0.514	0.883	**0.870**	0.888
Human carcinogenic toxicity	kg 1,4-DCB	2.50	2.07	**2.02**	3.10	**2.38**	2.94
Land use	m2a crop eq.	1.87E-02	**1.83E-02**	8.06E-02	1.64E-02	**1.15E-02**	3.44E-02
Mineral resource scarcity	kg Cu eq.	1.43E-03	**1.10E-03**	4.40E-03	1.51E-03	7.01E-04	**2.53E-04**
Fossil resource scarcity	kg oil eq.	2.56	2.53	**2.11**	0.51	0.430	**0.155**
Water consumption	m3	7.35E-03	**6.92E-03**	8.01E-03	2.12E-03	1.22E-03	**2.31E-04**
Cumulative Energy Demand	MJ/kg	119.50	119.80	**105.20**	20.33	19.30	**7.68**

AC: Activated Carbon, BC: Biochar and bold numbers show the lowest values for each impact categories.

emission, therefore this might have lowered the GWP results. Another reason that might affect the GWP results could be the furnace type to conduct this study. According to another study, different pyrolysis systems affect the GWP result (Puettmann et al., 2020). GWP of biochar derived from forest residues through Biochar Solutions Incorporated portable biochar system, Oregon Kiln, and Air-Curtain Burner were 0.25–0.31, 0.11, and 0.16 tons CO_2eq./tons, respectively.

3.2. Sensitivity analysis

A sensitivity analysis was conducted to determine the effect of transportation distance reduction and altering energy source to solar energy impacts on environment for the biochar and activated carbon production. For the first simulation, the distance from the farm (biomass waste transportation) to the pyrolysis lab was altered to 20 km (closer farm was selected) and transportation of produced adsorbent to WWTP was altered to 10 km (closer WWTP was selected). The comparison of the original scenario where (100% landfill BC and 100% landfill AC) with the new altered distances scenario are displayed in Table 3. It was observed that reduced distance lowered GWP 8.33 to 8.23 kg CO_2 eq. and for activated carbon production and 1.53 to 1.29 kg CO_2 eq. for biochar production. Reduced distance did not cause significant decrease in terms of CED for both adsorbents.

The second simulation involved varying energy generated from solar farms used for the heating and electrical processes (pyrolysis, drying, sieving, crushing, and activation) for each adsorbent. The comparison of the original scenario where natural gas used in the '100% landfill BC' and '100% landfill AC' with solar energy as energy source is displayed in and Table 3. Analysis result showed that utilizing solar energy as energy source reduced CED 119.50 to 105.2 MJ/kg (14% reduction) for activated carbon production and 20.33 to 7.68 MJ/kg (62% reduction) for biochar production. GWP reduced from 8.33 to 7.29 kg CO_2 eq. and 1.53 to 0.665 kg CO_2 eq. for activated carbon and biochar production respectively. Additionally, the stratospheric ozone depletion contribution was significantly reduced for both activated carbon and biochar by approximately 50% and 45% respectively. Reductions for both adsorbents were observed in both sensitivity analysis scenarios. However, a higher reduction in emissions were observed when the energy source was varied as observed in Table 3.

Therefore, it can be deduced that the environmental impacts from producing biochar and activated carbon are highly sensitive to varying the source of the energy utilized in the process. It is highly recommended that cleaner sources of energy should be utilized for adsorbent production for less environmental impact. On the contrary, a reduction in transportation of waste and adsorbent did not result in a significant change in terms of CED and GWP.

3.3. Economic assessment

Figure 5 (a-b) shows the costs associated with the biochar derived from date palm waste. Total fixed capital investment of biochar was found to be $161,400, and total production cost was estimated as

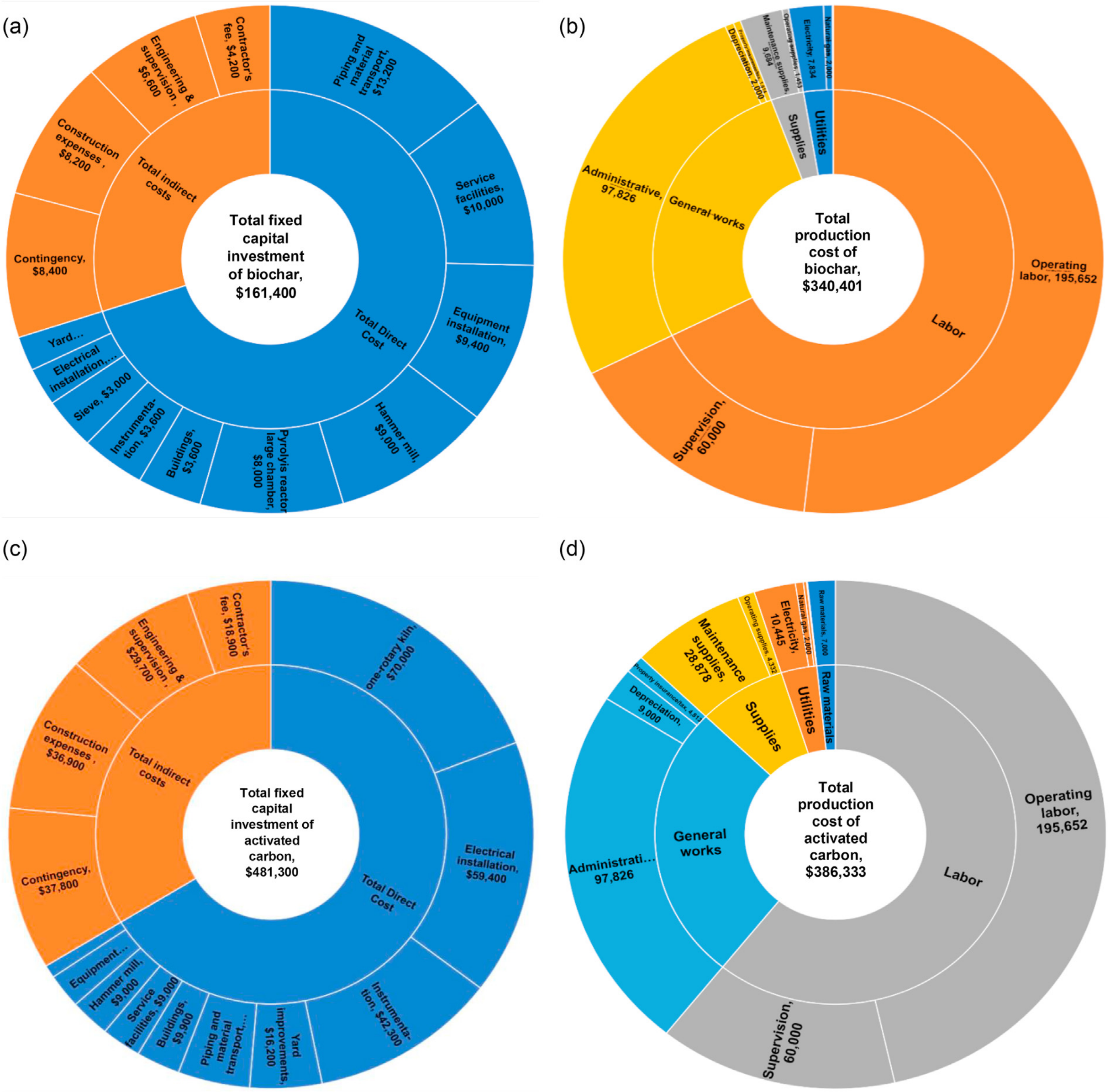

Figure 5. Total fixed capital investment breakdown of (a) biochar (c) activated carbon and total production cost breakdown of (b) biochar and (d) activated carbon.

Table 4. Net Present Value analysis for biochar and activated carbon.

	Years	Amount of cash flow	20% discount rate	Present value of cash flow ($)
Biochar				
Annual cash inflow	1 to 5	$ 340,401.22	2.991	$ 1,018,140.05
Initial investment	now	$ (161,400.00)	1	$ (161,400.00)
Net present value				$ 856,740.05
Activated carbon				
Annual cash inflow	1 to 5	$ 386,332.95	2.991	$ 1,155,521.85
Initial investment	now	$ (481,300.00)	1	$ (481,300.00)
Net present value				$ 674,221.85

$340,401. Based on a 1000 kg day^{-1} biochar production rate with 320 operating days annually, it is estimated that 320,000 kg of biochar is produced per annum and hence, the production cost is calculated as $1.06 per kg of product. Figure 5 (c-d) shows the costs associated with activated carbon. Total fixed capital investment of activated carbon was estimated as $481,300 and total production cost was found as $386,333. Based on a 900 kg day^{-1} activated carbon production with 320 operating days in a year, it is estimated that 288,000 kg of activated carbon is produced per annum, and hence the production cost per unit of activated carbon is calculated as $1.34 per kg. Table A1 shows the financial assessment of biochar derived from date palm waste and activated carbon derived from woody biomass.

The NPV analysis for biochar and activated carbon is summarized in Table 4. For the purpose of budgeting, the annual capital investment and the production cost of a manufacturing facility that produces biochar amount to $161,400 and $340,401. The results revealed that the NPV for biochar is positive ($0.86 million). A positive NPV value indicates that the investment proposal is acceptable (Lai and Ngu, 2020). The annual

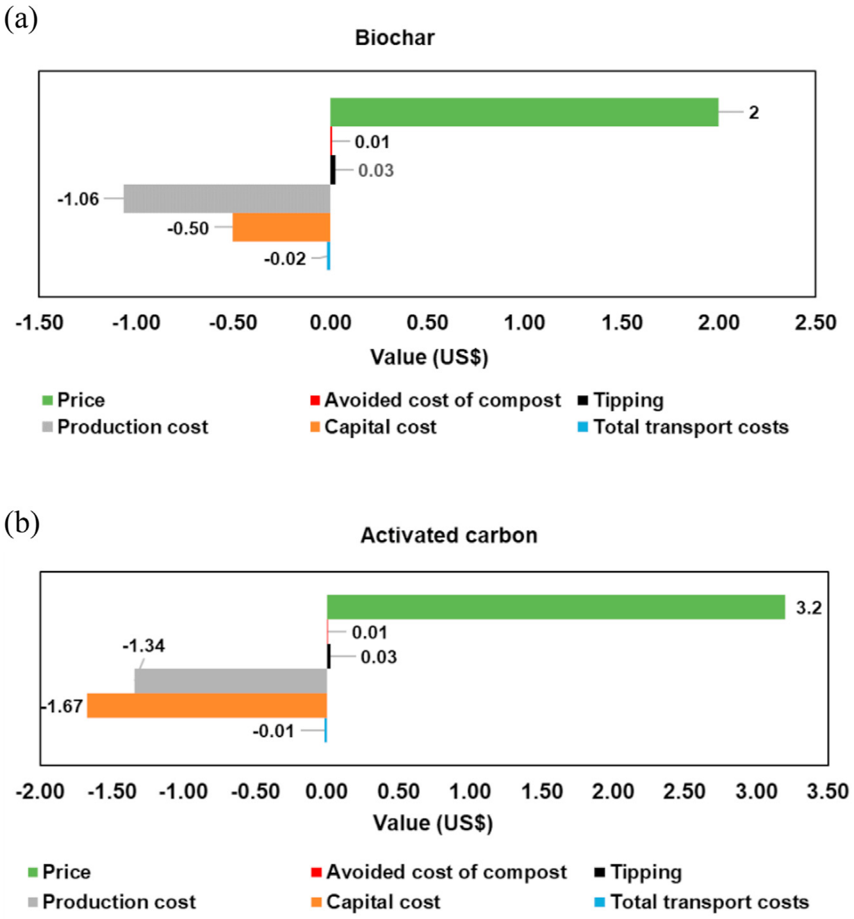

Figure 6. Breakdown of costs and revenues of (a) biochar and (b) activated carbon.

capital investment and the production cost of a manufacturing facility that produces activated carbon amount to $481,300 and $386,333. The results revealed that the NPV is also positive ($0.67 million) but lower than that of biochar.

Our results show that the date palm biochar has a much lower production cost per unit than activated carbon. Figure 6 (a-b) depicts the breakdown of the costs and revenues of date palm biochar and activated carbon. According to the International Biochar Initiative, the global average price of biochar (wholesale) was about $2.00 per kg in 2013 and 2014 (Jirka and Tomlinson, 2015). However, according to literature, the most cited sales price for biochar was lower such as $1.6 per kg (Nematian et al., 2021). The price of biochar is highly variable presently because its potential is still not fully explored, and the market is still not fully established (Dai et al., 2019). For the purpose of this assessment, a sale price of $2.00 per kg of biochar was used. As for activated carbon prices, commercial sources and those from literature reported a range between $0.34 to 22 per kg (Alhashimi and Aktas, 2017). Despite the higher price for activated carbon ($3.2) than biochar ($2.00) as retrieved from a study (Alhashimi and Aktas, 2017), one can infer that a profit of $0.45 per kg of biochar can be gained while a lower profit of $0.21 per kg of activated carbon might happen. This can be explained by the higher production and capital cost of activated carbon as compared to that of biochar's as Figure 6 (a-b) shows.

The financial implications of the sensitivity analysis i.e., reducing transportation distance and altering the source of energy to solar energy was also assessed. Reducing the transportation distance increased the profit gained per kg of biochar from $0.45 to $0.48 and from $0.21 to $0.24 for activated carbon. This was due to the transportation costs per kg dropping from US' 2 to US' 1for both biochar and activated carbon When the source of energy was switched to solar energy, the effect was slightly more profound with activated carbon; the profit per kg of biochar increased from $0.45 to $0.48 while that of activated carbon increased from $0.21 to $0.25. Consequently, the production costs dropped from $1.06 to $1.04 for biochar and from $1.34 to $1.30 for activated carbon. Based on the results of this study, it is highly recommended that cleaner sources of energy be utilized as they not only lessen the environmental impacts but also reduce the financial implications.

3.4. Performance analysis

When adsorption capacity of date palm biochar and other biochars derived from different feedstock and activated carbon are compared against different aqueous pollutants, it can be observed that biochar is comparable to activated carbon, and in some cases can give even higher adsorption capacities as shown in Table 5. Bansode et al. (2003) found that biochar derived from pecan shell gave an adsorption capacity of 64.2 mg/g for lead. Similarly, Kikuchi et al. (2006) found that activated carbon derived from coconut shell yielded maximum lead adsorption capacities of 76.6 mg/g. Compared to activated carbon, sesame straw derived biochar had superior lead adsorption capacities equivalent to 102 mg/g (Park et al., 2016). Additionally, biochar displayed promising adsorption capacities for pharmaceuticals such as SMX and Ibuprofen as shown in Table 5. However, there are certain factors which limits the applications of biochar as adsorbent. The adsorption efficiency of biochar is regarded not stable, and it fluctuates whereby activated carbon has a predictable and stable efficiency. Moreover, there exists limited information on the consistency of the performance of biochar since different raw materials for the production of biochar changes its features.

Table 5. Inorganics and organics removal using biochar and activated carbon.

Ion removed	Adsorbent- biochar	Adsorption capacity, mg/g	Adsorbent- activated carbon	Adsorption capacity, mg/g
Cu^{2+}	Corn straw derived biochar	12.52 (Chen et al., 2011)	Powdered activated carbon	1.80 (Regmi et al., 2012)
	Activated biochar	31 (Regmi et al., 2012)	Activated carbon	24.10 (Chen and Wu, 2004)
	Pig manure chemically treated biochar	6.80 (Kołodyńska et al., 2012)	Softwood derived activated carbon	6.35 (Han et al., 2013)
			Tannic acid immobilized activated carbon	2.73 (Üçer et al., 2006)
Zn^{2+}	Dairy manure-derived biochar	32.8 (Xu et al., 2013)	Modified activated carbon- sodium Diethyldithiocarbamates (SDDC)	9.9 (Monser and Adhoum, 2002)
	Corn straw derived biochar	11 (Chen et al., 2011)	Hardwood derived activated carbon	5.03 (Han et al., 2013)
			Tannic acid immobilized activated carbon	1.8 (Üçer et al., 2006)
Cd^{2+}	Activated biochar	34 (Regmi et al., 2012)	Powdered activated carbon	1.5 (Regmi et al., 2012)
	Pig manure chemically treated biochar	11.20 (Kołodyńska et al., 2012)	Tannic acid immobilized activated carbon	2.46 (Üçer et al., 2006)
Cr^{6+}	Banana peduncle biochar	114 (Karim et al., 2015)	Activated carbon derived from acid-treated coconut fibers	1.1–15.6 (Mohan et al., 2011)
Mn^{2+}	Farmyard manure-derived biochars	6.65 (Idrees et al., 2018)	Tannic acid immobilized activated carbon	1.73 (Üçer et al., 2006)
	Phosphoric acid pre-treated biochars (PBPB) derived from banana peels	2.03 (Kim et al., 2020)		
	Biochar derived from date palm waste-fronds and leaves	8.54 (Fseha et al., 2022)		
Fe^{2+}	PBPB derived from banana peels	32.99 (Kim et al., 2020)	Tannic acid immobilized activated carbon	2.80 (Üçer et al., 2006)
Pb^{2+}	Anaerobically digested sugarcane bagasse biochar	136 (Inyang et al., 2011)	Commercial activated carbon	7 (Cao et al., 2009)
NH_4^+	Polar chips derived biochar with Mg pretreatment	58.60 (Yin et al., 2019)	Avocado seed derived activated carbon	5.4 (Zhu et al., 2016)
	Presscake from anaerobic digestate	136.20 (Takaya et al., 2016)	Coconut shell derived activated carbon	2.3 (Boopathy et al., 2013)
	Biochar derived from date palm waste-fronds and leaves	49.76 (Fseha et al., 2021)		
NO_3^-	Biochar derived from date palm waste-fronds and leaves	4.39 (Fseha et al., 2022)	*Borassus aethiopum* derived activated carbon	8.99 (Koné et al., 2022)
PO_4^{3-}	Polar chips derived biochar with Mg pretreatment	89 (Yin et al., 2019)	Coir-pith activated carbon	7.74 (Kumar et al., 2010)
	Presscake from anaerobic digestate	30 (Takaya et al., 2016)	Date stones derived activated carbon	7.48 (El–Chaghaby and Abd El–Shafea, 2021)
	Biochar derived from date palm waste-fronds and leaves	26.90 (Fseha et al., 2021)		
Ni^{2+}	Date seed derived biochar	19.54 (Mahdi et al., 2018)	Almond husk derived activated carbon	4.89 (Hasar, 2003)
Sulfamethoxazole	Bagasse derived biochar	4.60 (Yao et al., 2018)	Coconut shell activated carbon	13.7 (Mansur et al., 2021)
Atenolol	Pine chips biochar	37.5 (Kim et al., 2016)	Granular activated carbon	4.8 (Haro et al., 2017)
Phenol	Chicken manure derived biochar	120 (Thang et al., 2019)	Bamboo charcoal powdered activated carbon	20.09 (Ma et al., 2013)
Ibuprofen (IBP)	Chili seeds biochar	26.13 (Ocampo–Perez et al., 2019)	Quercus Brantii (Oak) acorn activated carbon	96.15 (Nourmoradi et al., 2018)

4. Conclusion

In this study, the performance, environmental impacts, and economic assessment of date palm biochar were compared to woody biomass activated carbon under an equivalent functional unit (1 kg). The results showed that activated carbon in both 50-50% disposal and 100% landfilling disposal methods contribute more to environmental impact categories. The least environmental impact was observed for 100% landfilling disposal scenario for the biochar. The CED for activated carbon production was found almost 6 times higher than the energy required to produce date palm biochar. Date palm biochar GWP was found to be 1.53 kg CO_{2eq}/kg which was less than 8.96 kg CO_{2eq}/kg for woody biomass activated carbon and other activated carbons derived from different feedstocks found in the literature. A sensitivity analysis for activated carbon and biochar was conducted where two factors were varied: distance and source of energy. Utilizing solar energy as energy source reduced 14% and 62% in CED for activated carbon and biochar respectively.

For the economic assessment, our results showed that the date palm biochar production cost per kg was $1.06, and activated carbon was $1.34. In terms of the financial implications of the sensitivity analysis, it was found that switching to solar energy reduced production costs from $1.06 to $1.04 for biochar and from $1.34 to $1.30 for activated carbon. Therefore, it is recommended that studies can utilize renewable energy as the primary source for producing low-cost adsorbents.

Evaluation of the performance of biochar and activated carbon in the removal of pollutants in terms of adsorption capacity showed that date palm biochar is comparable to activated carbon, and in some cases even higher than that of activated carbon. In conclusion, date palm waste biochar showed comparable adsorption efficiency and superior environmental impact and cost effectiveness than activated carbon. Therefore, it can be a material of choice for the removal of pollutants in aqueous solutions effectively.

Declarations

Author contribution statement

Jamal Shaheen; Yohanna Haile Fseha: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Banu Sizirici: Conceived and designed the experiments; Wrote the paper.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

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