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Estimation of Poultry Litter and its Biochar Production Potential through Pyrolysis in Qatar

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One of the primary sources of waste in Qatar is animal waste, which includes poultry litter. Annually, Qatar produces approximately 0.83 x 10^6 t of poultry litter. Consequently, there is a need for a more sustainable waste treatment approach to handle it. Hence, this study's principal objective is to investigate the suitability of poultry litter as a feedstock for pyrolysis, with a specific emphasis on its potential for biochar generation. The physicochemical evaluations of poultry litter were performed. The potential for biochar formation from poultry litter was assessed using empirical equations at two different pyrolysis temperatures, namely 250 °C and 500 °C. Additionally, an economic analysis was conducted in order to ascertain the potential revenue generated by biochar derived from poultry litter. The composition of poultry litter, characterised by a moderate volatile content of 60 % and a fixed carbon content of 16 %, along with a moderate higher heating value (HHV) of 16 MJ/kg, indicates its potential suitability as a highly suitable feedstock material for biochar generation through pyrolysis. According to the findings of the technical analysis, biochar yields of up to 50 % and 31 % can potentially be achieved at 250 °C and 500 °C, respectively. Moreover, the findings of the study indicate that Qatar has the capacity to generate up to 0.35 x 10^6 t of biochar annually from its poultry litter. Additionally, the economic analysis suggests that the country can generate annual revenue of about 69 x 10^6 USD from the selling of biochar.

1. Introduction

Biochar includes carbon and plant nutrients that can be utilised to enhance nutrient-poor plants and restore depleted soil. Biochar additions have been demonstrated to impact the chemical, physical, and biological components of soil. On the other hand, worldwide population growth, economic expansion, and modernisation are all leading to a rise in worldwide waste production, with Qatar being no exception. Primary waste sources in Qatar include municipal solid waste (MSW) and animal waste such as dairy manure, sheep manure, and poultry litter. Compared to MSW, animal manures contain high levels of nutrients and low levels of heavy metals. Further, animal manures have moderate levels of carbon and volatile content, making them appropriate for use as sources of fuel and for the production of biochar. Qatar's increasing arable land requires sustainable natural soil conditioners such as biochar.

This study explores the possibility of biochar production from poultry litter because of the abundant availability of poultry litter in Qatar. The litter is primarily composed of organic carbon, with traces of nitrogen, phosphorus, potassium, magnesium, calcium, sulphur, iron, and manganese. Traditionally, it is employed as a fertilizer as such, while the dried litter is utilised as a fuel. Recently, it has been used to produce syngas, biochar, activated carbon, and other products. The production of biochar from poultry litter is accomplished using pyrolysis, a process that involves heating dry litter between 250 and 600 °C in an oxygen-deficient environment with modest heating rates and extended residence time (Elkhalifa et al., 2022). The quantity and characteristics of biochar are primarily determined by temperature and heating rate. Various pyrolysis parameters, including residence time, feedstock size, reactor type, and catalyst, also influence the properties of biochar.

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In this study, the pyrolysis prediction model is used to forecast pyrolysis products' generation potential. The model is based on the pyrolysis reactions. The model covers pyrolysis variables like temperature and heating rate. Many investigators have confirmed and effectively utilised this model to predict the distribution of pyrolysis products (Neves et al., 2011). The pyrolytic kinetics model followed elsewhere has been modified in the present study to predict the yields of biochar, bio-oil, and syngas (Song, 2016).

There is a notable lack of detailed documentation on the production of poultry litter in the country, the possibilities of generating biochar from it, and the potential financial benefits linked to biochar production.

Considering the above, the following objectives are set for this research endeavour:

i. To quantify poultry litter waste generation in Qatar;
ii. To estimate biochar generation potential from the available poultry litter;
iii. To determine the possible revenue from biochar production in Qatar.

The study followed the project workflow outlined below: gathering poultry litter availability data in Qatar, collecting characterisation analysis data of poultry litter, conducting techno-economic analyses, and estimating the potential for biochar generation and biochar revenue.

2. Materials & methods

Poultry litter waste was chosen as the feedstock for this study.

2.1 Quantification of poultry litter waste generation

Government statistics reports (Planning and Statistics Authority (PSA), 2021) and literature studies (Barker et al., 2002) on livestock manure production were reviewed.

2.2 Techno-economic analysis

The current study utilised empirical equations based on proximate and elemental analysis results to calculate the yield of biochar, syngas, and bio-oil. Figure 1 illustrates the schematics of the poultry litter pyrolysis process.

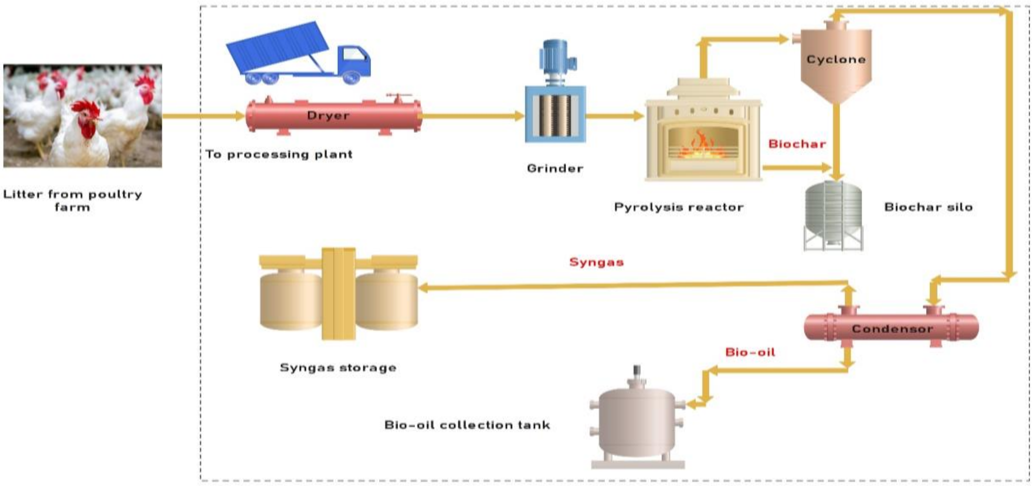

Figure 1: A simplified flow diagram illustrating poultry litter pyrolysis process.

The initial stage of pyrolysis, which is responsible for producing biochar, normally happens between 250 and 500 °C. Thus, in the present study, only these particular temperatures were considered.

A few key assumptions were established throughout the process of developing the prediction model.

i. An isothermal reactor operating in a N_2 environment pyrolyses poultry litter;
ii. The poultry litter undergoes pyrolysis and is converted into water, volatile fractions (bio-oil components), syngas (H_2, CH_4, CO, and CO_2), biochar, and ash during the initial drying phase of the reaction;
iii. The synthesis of these products occurs in the first stage of pyrolysis (Equations 1-3) (Swagathnath et al., 2019);
iv. As the temperature rises in the subsequent stages, the bio-oil is further cracked into syngas;
v. Depending on the composition of the poultry litter, the syngas products fracture into various gaseous components during this phase.

$$Bio-oil\ yield = Y_{tar,F} + Y_{H_2O,F} + Moisture\ content\ of\ samples \quad (1)$$
$$Pyrogas\ yield = Y_{H_2,F} + Y_{CO,F} + Y_{CH_4,F} + Y_{CO_2,F} \quad (2)$$
$$Biochar\ yield = 0.106 + 2.43 * \exp(-0.66 * T * 10^{-2}) \quad (3)$$

The equations below (4-16) were applied to estimate the economic parameters of the poultry litter pyrolysis process (Parthasarathy et al., 2023b).

$$Capital\ expense\ (CAPEX) = \sum Purchased\ equipment + Equipment\ setting + Piping + Civil + Steel + Instrumentation + Electrical + Insulation + Paint + Contract\ fees + General\ and\ administrative\ overheads + Contingencies \quad (4)$$

$$Working\ capital = \frac{5\ \%\ of\ CAPEX}{lifetime} \quad (5)$$

$$Operating\ expense\ (OPEX) = \sum Feedstocks + Operating\ charges + Labor\ charges + maintenance\ cost + Plant\ overhead + General\ and\ admistrative\ overheads \quad (6)$$

$$Subtotal\ OPEX = \sum Operating\ charges + Labor\ charges + maintenance\ cost + Plant\ overhead \quad (7)$$

$$Labor\ charges = (Operators\ per\ shift\ X\ Operator\ charges) + (supervisors\ per\ shift\ X\ Supervisor\ charges) \quad (8)$$

$$Operating\ charges = \frac{25\ \%\ of\ labor\ charges}{Period} \quad (9)$$

$$Plant\ overhead = \frac{50\ \%\ of\ labour\ charges\ and\ maintenance}{Period} \quad (10)$$

$$General\ and\ administrative\ cost = \frac{8\ \%\ of\ subtotal\ operating\ cost}{Period} \quad (11)$$

$$Return\ on\ investment\ (ROI)\ (\%) = \frac{Net\ profit}{CAPEX} \quad (12)$$

$$Payback\ period\ (years) = \frac{CAPEX}{Cash\ inflow} \quad (13)$$

$$Minimum\ selling\ price\ (MSP)\ \left(\frac{USD}{kg}\right) = \frac{CAPEX + \sum_1^{lifespan}(Opex\ (1 + Discount\ Rate)^{-lifespan})}{\sum_1^{lifespan}(fuel\ yield(1 + Discount\ Rate)^{-lifespan})} \quad (14)$$

$$Cost_{design} = Cost_{base} \cdot \left(\frac{Capacity_{design}}{Capacity_{base}}\right)^{scaling\ factor} \cdot Installing\ factor \quad (15)$$

$$Cost_{design,\ USD_{2019}} = Cost_{design,\ USD_i} \cdot \left(\frac{CEPCI_{2019}}{CEPCI_i}\right) \quad (16)$$

Table 1. provides the list of assumptions employed for the economic analysis. The assumptions were made on Qatar scenario and based on the year 2021 (Parthasarathy et al., 2023a).

Table 1: Assumptions employed for the economic analysis.

Parameters	Values
Proposed lifetime of the plant	25 years
Discount rate	20 %
Annual feed capacity	830000 t
Plant operating hours in a year	8,000 h/y
Raw material source to plant distance	100 km
Cost of poultry litter	30 USD/t
Cost of 1 unit of electricity	0.035 USD/kwh
Cost of water utility	1.479 USD/m^3
Cost of N_2 gas	0.15 USD/kg
Market price of biochar	0.2 USD/kg
Market price of Bio-oil	0.4 USD/kg
Market price of Syngas	0.056 USD/kg
Drying efficiency of the drier (%)	90 %
Flow rate of nitrogen for the process	5 litre/min. t

3. Results and discussion

3.1 Quantification of poultry litter waste generation

Approximately 25,927,600 poultry livestock are raised in Qatar. The availability of poultry litter is determined based on the assumption that a poultry produces 32 kg of litter each year. Based on this, the amount of poultry litter is estimated to be 830,000 t/y.

3.2 Techno-economic analysis

The proximate, elemental, and thermal analyses outcomes of poultry litter are provided in Table 2.

Table 2: Typical characteristics of poultry litter waste in Qatar.

Proximate analysis (%)	Air-dried basis
Moisture	8.02
Volatile matter	60.31
Fixed carbon	16.25
Ash	15.42
Elemental analysis (%)	**Dry-basis**
Carbon	40.02
Hydrogen	5.38
Nitrogen	5.57
Oxygen	33.53
Sulphur	0.10
Chlorine	0.00
Ash	15.40
LHV	14.89
Reference	(Kantarli et al., 2016)

A high volatile composition (60 %) and a moderate fixed carbon composition (16 %) implies that the litter can serve as a good fuel as such. However, it has a high ash content (15 %) which may reduce the energy content of the manure. High ash content is also expected to cause ash handling issues as slagging, corrosion, *etc*. The manure possesses a moderate elemental carbon content (40 %) which also confirms its suitability as a fuel. The bothering aspect of the manure is its nitrogen content (6 %), which may lead to the emissions of NOx and NH_X.

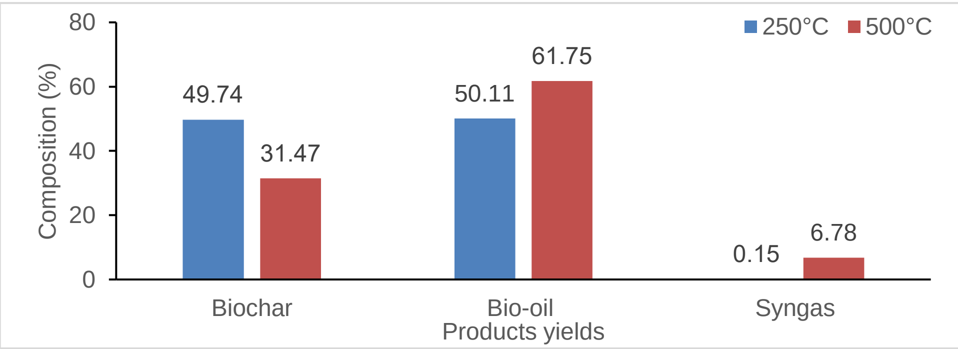

Figure 2. Effect of pyrolysis temperature (250 °C and 500 °C) on the yields of biochar, bio-oil, and syngas.

The effect of pyrolysis temperature (250 and 500 °C) on the yields of biochar, syngas, and bio-oil is illustrated in Figure 2. As the temperature increased from 250 to 500 °C, the production of biochar reduced. The rise in temperature resulted in higher yields of bio-oil and syngas. The reduction in biochar production is a result of carbon reacting with other elements to form volatile hydrocarbons. The enhanced production of bio-oil and syngas is due to the breakdown of C-H and of C=H, resulting in the formation of more volatile substances. The interaction between carbon, hydrogen, and oxygen also plays a role in increasing the production of bio-oil and syngas. An in-depth economic analysis was carried out to assess the revenue possibilities of biochar production in Qatar. The estimated economics parameter values attained for the two pyrolysis processes (250 °C and 500 °C) are provided in Table 3.

Table 3. Economic parameters for pyrolysis plants operated at 250˚C and 500˚C.

Temp. (°C)	CAPEX (10^6 USD)	OPEX (10^6 USD/y)	Sales (10^6 USD/y)	Profit (10^6 USD/y)	NPV (10^6 USD)	ROI (%/y)	Payback period (y)	Biochar MSP (USD/kg)
250	164.44	37.07	73.35	36.28	15.07	0.22	4.53	0.18
500	164.70	37.16	80.21	43.05	48.29	0.26	3.83	0.04

The variations in CAPEX and OPEX between the two processes are minimal, while the other parameters displayed a notable difference. Pyrolysis carried out at 500 °C resulted in higher sales and profits compared to pyrolysis at 250 °C due to the increased generation of biooil, which has a higher market value than biochar. A higher NPV was achieved at 500 °C, confirming that the process carried out at this temperature will be more profitable. An elevated ROI at 500 °C suggests that the process would yield greater profits compared to a process conducted at 250 °C. A shorter payback period at 500 °C indicates that the initial investment for the procedure can be recovered within 4 years. Both processes provide biochar at a price lower than the market price of biochar, which is 0.2 USD/kg. The difference in biochar MSP between the two processes is mainly attributed to the higher bio-oil production at 500 °C and the elevated market value of bio-oil at 0.4 USD/kg. It could be concluded that operating the process at 500 °C could lead to increased profitability but reduced biochar production.
Table 4. shows the biochar generation and revenue potential from poultry manure available in Qatar. The amount of dry waste feed is determined based on the assumption that it contains only 10 % moisture and is acceptable for pyrolysis treatment.

Table 4. Production of biochar and potential income from poultry litter waste in Qatar.

Available poultry litter quantity (t/y)	Dry poultry litter quantity (t/y)	Estimated biochar yield* (%)	Estimated biochar yield* (%)	Biochar production potential (t/y)**		Expected annual biochar revenue (10^6 USD)	
		at 250 °C	at 500 °C	at 250 °C	at 500 °C	at 250 °C	at 500 °C
829,683	696,934	49.74	31.47	346,628	219,333	69.30	43.90

* **c**omprising both biochar and ash
* assuming 100 % poultry manure collection

The amount of dry poultry manure available in the country is estimated to be 696,934 t/y. The pyrolysis process conducted at 250 °C and 500 °C is anticipated to generate 346,628 t/y. and 219,333 t/y. respectively. Conducting the pyrolysis process at 250 °C will fetch a biochar annual revenue potential of 69.30 x 10^6 USD while performing the process at 250 °C will fetch a biochar annual revenue potential of 43.90 x 10^6 USD.
The projected biochar production quantity and biochar revenue potential is based on only two temperatures- 250 °C and 500 °C. Pyrolysis temperature has a substantial impact on both the quantity and quality of biochar produced. However, other factors such as feedstock type, feedstock size, reactor design, and pyrolysis residence time also influence biochar production and quality. Higher pyrolysis temperatures usually result in lower biochar production, larger surface areas, higher ash content, minimal overall surface charge, improved water retention capacity, and elevated pH levels (Abdelaal et al., 2021). Also, high pyrolysis temperatures increase carbon composition of biochar and reduces oxygen and hydrogen compositions of biochar. However, pyrolysis experiments do need to be performed at high temperatures as moderate temperatures may well be sufficient to produce good quality biochar that can be applied for soil conditioning and carbon storage. Therefore, it is recommended to initiate tests for biochar production through pyrolysis at lower temperatures.

4. Conclusions

Qatar generates around 0.83 x 10^6 t of poultry litter each year. Therefore, a more sustainable waste treatment approach is required for managing it. Hence, this study's principal objective is to investigate the suitability of poultry litter as a feedstock for pyrolysis, with a specific emphasis on its potential for biochar generation. The potential for biochar formation from poultry litter was assessed using empirical equations at two different pyrolysis temperatures, namely 250 °C and 500 °C. Additionally, an economic analysis was conducted in order to ascertain the potential revenue generated by biochar derived from poultry litter. According to the findings of the technical analysis, biochar yields of up to 50 % and 31 % can potentially be achieved at 250 °C and 500 °C, respectively. Moreover, the findings of the study indicate that Qatar has the capacity to generate up to 0.34 x 10^6 t of biochar annually from its poultry litter. The economic analysis indicates that both the processes offer a biochar MSP lower than the market price of biochar (0.2 USD/kg). Furthermore, the analysis indicates that operating the pyrolysis process at 500 °C helps to achieve a better profitability than operating the process at 250 °C. It also suggests that the country can generate annual revenue of about 69 x 10^6 USD from the selling of biochar. The study's findings are expected to enhance future research endeavours and decision-making processes concerning poultry litter waste handling and valorisation.

Nomenclature

T –Pyrolysis temperature, °C
$Y_{CO,F}$ – CO gas yield obtained from the pyrolysis of feed, kg
$Y_{CO2,F}$ – CO_2 gas yield obtained from the pyrolysis of feed, kg
$Y_{CH4,F}$ – CH_4 gas yield obtained from the pyrolysis of feed, kg
$Y_{H2,F}$ – H_2 gas yield obtained from the pyrolysis of feed, kg
$Y_{H2O,F}$ – Water yield obtained from the pyrolysis of feed, kg
$Y_{tar,F}$ – Tar yield obtained from the pyrolysis of feed, kg

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