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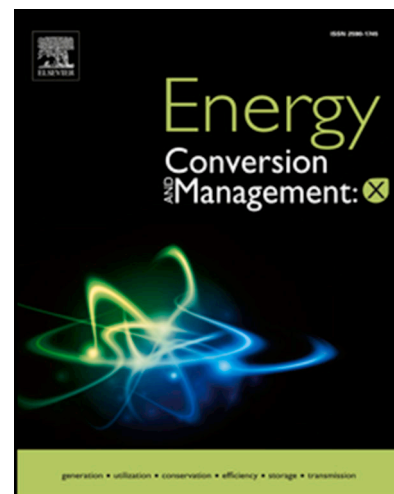
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Developing biochar from potential wastes in Qatar and its revenue potential

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Abstract:

Global population growth, booming economies, and modernization are all contributing to increased waste generation, including in Qatar. A more sustainable waste treatment strategy is therefore essential to reaching Qatar's National Vision 2030. Qatar's main waste sources are municipal solid wastes and animal wastes. Both sources have high energy/chemical content and can be converted to fuels and value-added products, particularly biochar. As Qatar continues to expand its arable land, biochar has become one of the most sought-after commodities. As a result, the primary goal of this study is to identify wastes produced in large quantities in Qatar and quantify them. The secondary goal of the research is to estimate the amount of biochar that can be produced from the wastes using pyrolysis technique, as well as the country's biochar revenue potential. A life-cycle assessment of biochar production from all wastes is also performed. Furthermore, the paper discusses market intervention and carbon trading, as well as concerns and limitations associated with biochar application. The findings indicate that Qatar produces 1.8 MT of food waste, the most of any waste produced in the country. Wastepaper has the highest biochar production rate of any waste. It is expected to produce 534,969 T and 224,286 T of biochar at 250°C and 500°C, respectively. Among the waste feeds, wastepaper has the greatest potential for

generating income from biochar. Its potential revenue is pegged at 107 million USD for 250°C and 45 million USD for 500°C annually.

Keywords: *Qatar; waste sources, pyrolysis, biochar, biochar revenue potential*

1. Introduction

In spite of the fact that biochar (charcoal) is a relatively new innovation in research, the application of biochar for soil improvement is not new [1]. The well-known "Terra Preta Soils" are a good illustration. Biochar has recently been considered as an agricultural amendment to improve agricultural productivity and sustainability [2]. It contains not only carbon but also plant nutrients, which are used to supplement nutrient-deficient plants and reclaim degraded soil [3]. Biochar amendments have been shown to influence soil's chemical, physical, and biological properties. It also mitigates the negative effects of drought and salt stress in arid environments. Furthermore, it can be used to remediate organic and inorganic contaminants in water and soil.

Pyrolysis (slow) is the primary thermochemical method applied to generate biochar, which involves thermally decomposing biomass materials in an oxygen-deficient atmosphere at temperatures between 250 and 600°C using long solid residence times and low heating rates [4–6]. The properties of biochar are largely determined by the pyrolysis process operating parameters and production variables such as heating rate, temperature, and feedstock characteristics [7]. It has been reported that virtually any biomass material can be used to generate biochar [8]. This entails biomass derived from plant vegetations including forest, agricultural, energy, or aquatic crops, biomass wastes derived from the processing of biomass materials, including husks, sawdust, peels, bagasse, and organic residues, including livestock manure, and sewage sludge [9].

Biochar agricultural application results in numerous environmental, social, and economic benefits. The environmental advantages of biochar include carbon sequestration, decreased greenhouse gas (GHG) emissions, restoration of infertile lands, water retention, adsorption of pollutants to clean up streams, *etc.* [10].

Large-scale production of biochar results in agronomic as well as economic gains. Application of biochar results in improved plant growth and product yield. Water retention and moisture adsorption nature of biochar significantly water intake of plants which in results in the drastic reduction of irrigation costs. Further, biochar is a marketable bio-product so as bio-oil and syngas which can be used in many commercial applications. Above all, biochar can be promoted by enacting a CO₂ sequestration payment policy.

Apart from agronomical applications, biochar due to its versatile properties relating to its structure, composition, and reactivity is used in many industries. Biochar is useful in wastewater treatment plants for adsorbing trace elements and pollutants. A high surface area and adsorption capacity of biochar can also reduce pollutants in wastewater significantly. Chemical industries use biochar as catalysts for cleaning syngas, especially for removing tar. A variety of microorganisms have been successfully inoculated using biochar, including *Azotobacter*, *Bacillus*, *Pseudomonas*, and *Rhizobium*. In electronics industries, biochar is used as electrodes for supercapacitors since it has a high surface area, a wide mesopore, and a high conductivity. It is also finding its application in the making of dye-synthesized solar cells. The long-term use of activated charcoal in humans to treat acute poisoning and digestive disorders suggests the potential for using biochar in medical fields. In the cosmetic industry, it is used as a cleansing agent. In addition, biochar is used as a feed supplement to improve the health of animals. In textile industry, they are used as catalyst support materials in the treatment of dyeing and printing wastewater. Biochar is used in the construction industry as a building material, as well as to insulate buildings and control humidity because of its low thermal conductivity and capacity to absorb water six folds its weight.

The growth of the world's population, the booming economy, and modernization are all contributing to increased waste generation, including in Qatar. There are three main waste sources

in the world: agricultural, forestry, and municipal solid wastes (MSW) (see **Figure 1**) [11]. However, the main sources of waste in Qatar are MSW and animal waste. The energy/chemical content of these sources is high, which makes them useful as fuel sources and for the production of value-added products, such as biochar. With Qatar's continued expansion of arable land, biochar has become increasingly popular.

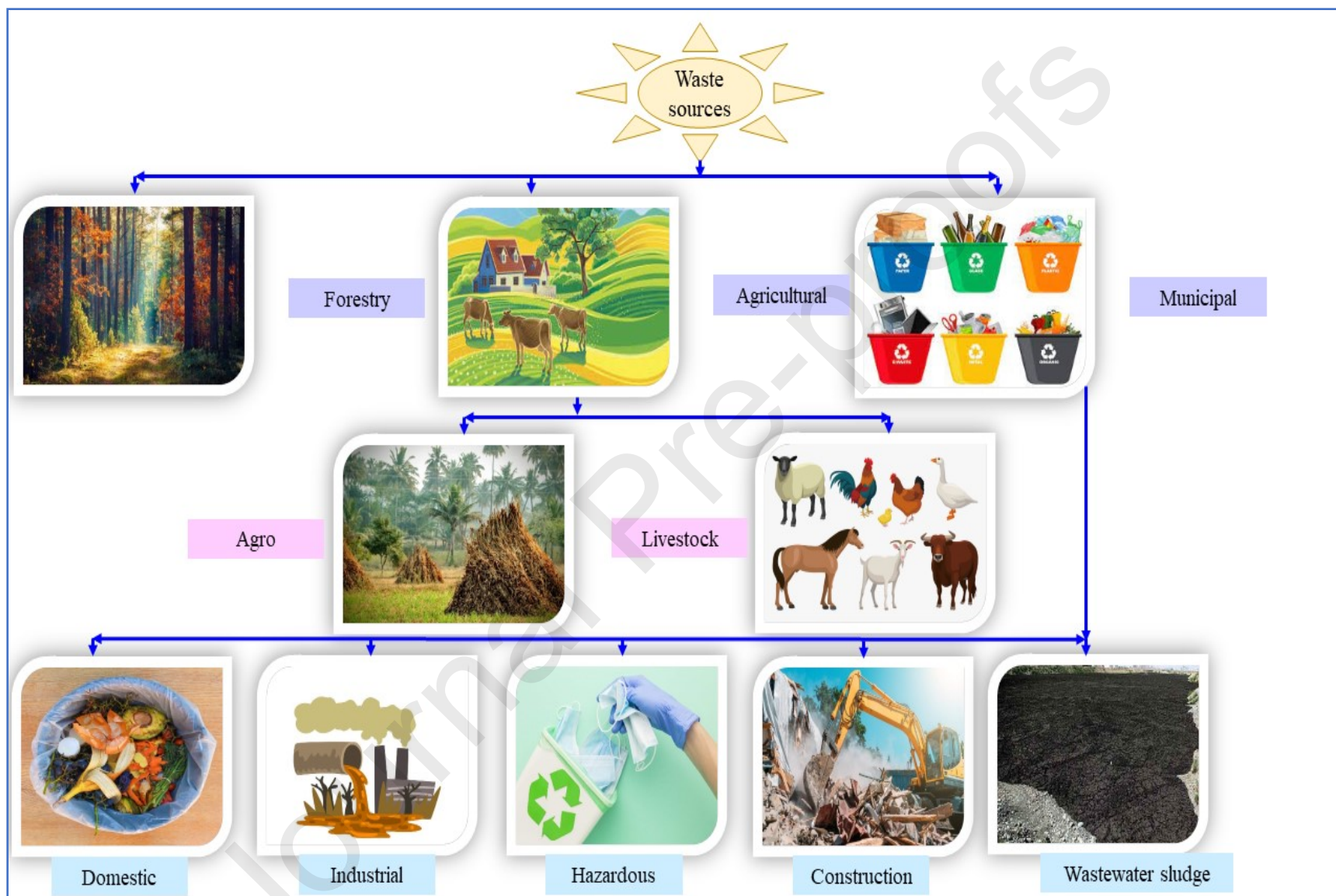


Figure 1. General classification of the waste sources.

One of the major impediments to Qatar's waste valorisation development is a lack of knowledge about its waste availability potential. Assessment of waste availability could help direct industry development strategies, policymakers, and stakeholders. This type of assessment is critical in determining the energy potential and the consequences of producing and consuming these resources. As a result, accurate waste source estimates are critical for decision-making and policymaking. Numerous studies have been conducted in various regions and countries to determine the energy potential of various agricultural, forestry, and municipal wastes [12]. **Table 1** discusses in greater detail the objectives and key findings of few previous studies.

Table 1. Objectives of few previous studies.

S.no	Reference	Estimation of waste availability	Estimation of product/energy generation	Estimation of product revenue potential	Objective	Findings/Inference
1.	[13]	✓	✓	✗	This study aimed to calculate the volume of solid and animal waste produced in Jordan as well as their potential for energy.	The total heating value of animal and olive solid wastes was discovered to be 6600 million MJ. This amount is equivalent to 157 KT of oil (toe).
2.	[12]	✓	✓	✗	The study looked into Jordan's biomass resource potential for heat/power production and biogas synthesis.	Jordan generates more than 6 MT of waste per year. Yearly biogas and power potential are 313 MCM and 847 GWh, respectively.
3.	[14]	✓	✓	✗	The goal of this work is to demonstrate the feasibility of using biomass residues to produce biogas in Greece and China.	Greece produces 10 MT of agricultural residues, 26 MT of animal manure, and 13 MT of agro-industrial residues per year. On the other hand, China produces 860 MT of agro wastes, 216 MT of animal manure, and 214 MT of agro-industrial residues each year. According to the theoretical estimates, Greece and China can produce 77 TWh and 5500 TWh of energy, respectively.
4.	[15]	✓	✓	✗	The study aims to estimate the amount of livestock waste produced and the	The yearly total livestock waste generated from commercial-scale

					potential for biogas generation in China.	husbandry feedlots was projected at 141 MT, which measures to a biogas potential of 61 billion m ³ .
5.	[16]	✓	✓	✗	The project intends to estimate biogas yield from municipal waste, feedstock, vinasse, and wastewater routes between 2030 and 2050.	According to the study, biogas production could increase from 5 million cubic meters per day of methane in 2030 to 20 million in 2050.
6.	[17]	✓	✗	✓	Based on 2014 data, the study attempts to estimate metal recovery potential from e-waste in Australia.	The metal recovery value from e-waste was estimated to be around USD 370 million.
7.	[18]	✓	✓	✗	The goal of this study is to estimate the biogas potential of selected livestock manure in Vietnam.	In 2020, the total biogas energy potential from livestock manure was estimated to be 127,000 TJ y ⁻¹ .
8.	[19]	✓	✓	✗	The project aims to calculate the biogas production from household waste and livestock manure in Iran.	The findings indicated that using livestock manure and rural wastes, Iran can produce 2740 million m ³ of biogas per year.
9.	[20]	✓	✗	✓	The study intends to quantify and characterize the MSW generated in Indonesia's Dumai Timur District, as well as to assess the economic potential of inorganic solid waste.	The findings revealed that 777,273 T/year is the estimated total amount of household waste produced in the region. The collection of inorganic waste, which includes plastic, paper, and metal, has a total economic potential of USD 55,660.

10.	[21]	✓	✓	✓	The potential for power generation as well as the financial and environmental advantages of biochemical methane production from municipal solid waste are estimated in this paper. 63 MW_e of electric power could be produced by establishing biowaste digestion plants with power generation facilities in the city, which is estimated to release 5600 T of methane into the atmosphere annually. The generated power can be sold for about 2.6 million USD in revenue each year.
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It is widely acknowledged that there is a significant dearth of comprehensive documentation in the international community of literature concerning the precise documentation of the overall volumes of organic waste accessible within a nation, the extent to which value-added commodities can be derived from said waste, and the potential financial gains associated with the production of said commodities. For *e.g.* the table above illustrates that numerous studies have looked into the quantity of accessible waste and its capacity to generate products or electricity. However, only a limited number of studies have assessed the potential income generation of a specific product derived from available waste. The current study exemplifies a specimen of such a composition. In consideration of the aforementioned, this research endeavour seeks to accomplish the following objectives:

- i. To identify and quantify significant sources of waste in Qatar;
- ii. To assess the potential for generating biochar from the waste sources in the country;
- iii. To estimate the potential revenue generated from biochar production in Qatar;
- iv. To evaluate and compare the economic viability of biochar generation from different waste sources;
- v. To assess and compare the life cycle analysis of biochar production from these waste sources;
- vi. To provide insights into market intervention and carbon trading in relation to biochar;
- vii. To discuss the limitations associated with the application of biochar.

The implementation of a quantitative assessment of waste and the calculation of biochar production has the potential to enhance resource utilisation and generate revenue in Qatar, thereby making a significant contribution to the economic development of the nation. This study aims to

offer policymakers significant insights, encompassing potential solutions for forthcoming legislative reforms, as well as the advancement of recycling sectors in Qatar and the MENA region.

2. Identification and quantification of significant waste sources in Qatar

Qatar does not have any forest and hence it has no forestry waste [22]. However, it generates agricultural wastes as it grows some vegetation and houses many livestock. It produces more livestock waste when compared to agro wastes as the agricultural sector is still at an initial stage of development. Although Qatar has a cultivable land of 65,000 hectares, only 12,907 hectares of land is utilized for cultivation [23]. This is due to adverse weather conditions, poor soil quality, and the large shortage of irrigation water [24].

2.1. Major waste sources in Qatar

In spite of its hostile environment, the country produces significant quantities of dates, vegetables, green fodder, vegetables, cereals, and fruits. The country's agro wastes are mainly from the date palms. The livestock wastes in Qatar are chiefly from cows, sheep, goat, poultry, camel, and horse livestock. Qatar produces a huge quantity of MSW. Its major municipal wastes are food waste, waste sludge, paper waste, textile waste, and waste tyre. An approximate estimation of wastes produced in Qatar is illustrated in **Figure 2**.

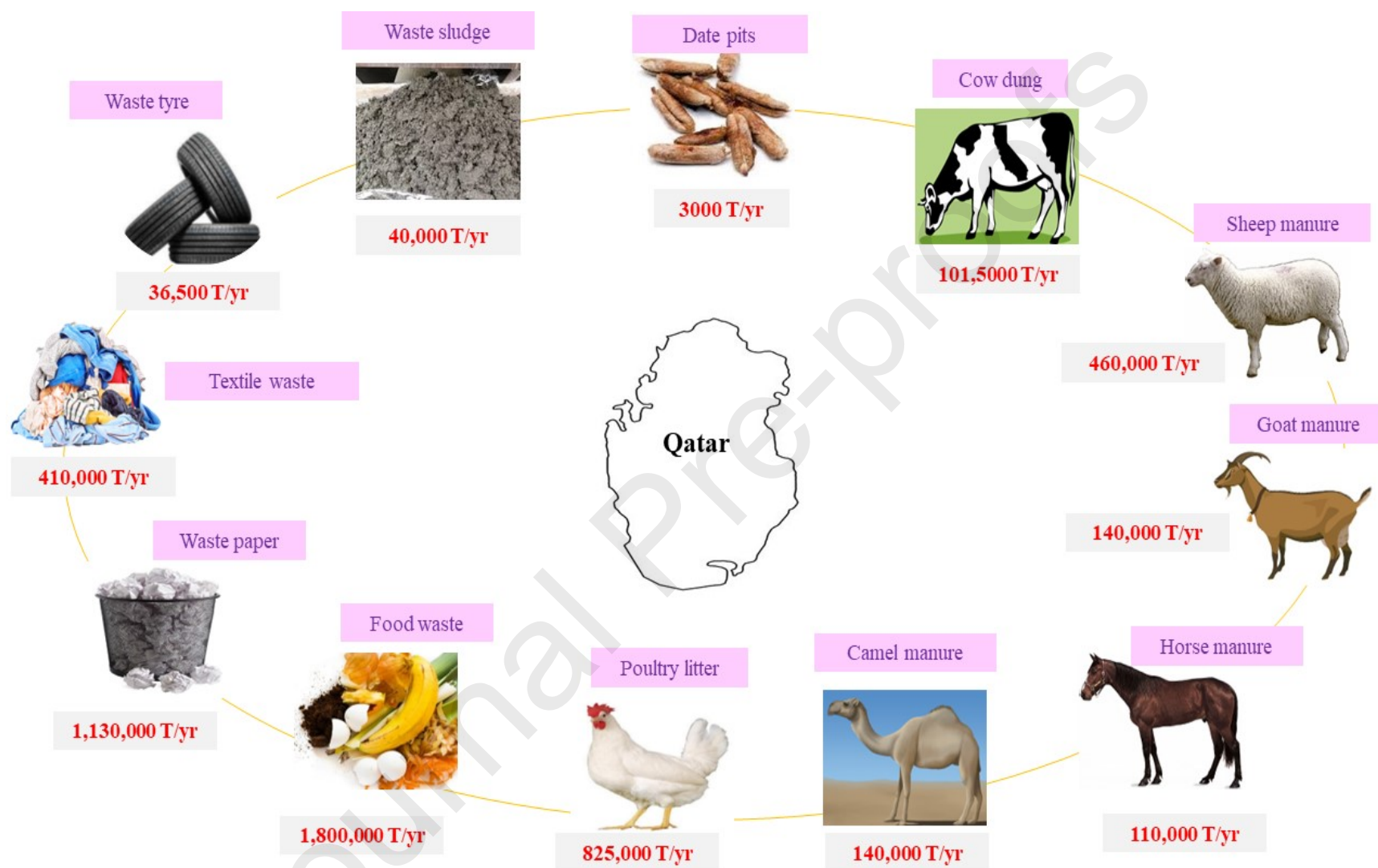


Figure 2. Wastes produced in Qatar.

2.1.1. Pyrolysis feedstocks blending

Co-pyrolysis is an alternative waste management and pollution elimination process that produces a solid material (biochar) that can be employed for energy generation and fertilizer application. It is a pyrolysis method that employs at least two carbon-rich fuel sources. Organic wastes such as coal, animal manure, agricultural waste, municipal waste, and animal manure are most often used as co-pyrolysis feedstocks [25,26].

The process's primary advantage is that it can efficiently address waste disposal issues because it can handle a lot of waste at once. The fact that it guarantees a consistent supply of feedstock is another benefit [27]. Wastes from animal and municipal sources are plentiful in Qatar, whereas wastes from plant biomass are scarce. Combining all of the aforementioned sources will therefore ensure the long-term availability of pyrolysis feedstocks in Qatar. Another key advantage of using the co-pyrolysis method is the ability to significantly reduce waste volume as more waste is used as feed sources [28]. In addition, it eases the necessity for a landfill, cuts waste handling and processing costs, and resolves many environmental issues. The combined effect of co-pyrolysis, which typically results in higher product quality and fewer pollutant releases, is another distinctive feature of the process [29]. The water content of the blend can be significantly reduced by combining plant, animal, and municipal wastes, which cuts down on costs and drying time. Furthermore, blending different waste sources contributes to social sustainability by creating new jobs.

In light of the above benefits, a multi-feed feedstock scenario is considered in this study (see **Table 2.**) considering the diverse waste feedstock availability in Qatar. A discussion of the results of multi-feed (blend) feedstock is provided in the sections below.

Table 2. presents the composition of wastes available in Qatar.

Wastes in Qatar	Their availability (%)
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Date seeds	0.06
Cattle manure	1.95
Sheep manure	8.85
Goat manure	2.69
Horse manure	2.12
Camel manure	2.69
Poultry litter	15.88
Food waste	34.64
Wastepaper	21.75
Textile waste	7.89
Waste tyre	0.70
Wastewater sludge	0.77
Total	100

2.2. Physico-chemical properties of prominent wastes in Qatar

Regardless of the waste valorisation process, the study of feedstock properties is critical for predicting product composition and resolving operational issues that may arise during the transformation process. The proximate, ultimate, and heating value analysis results of the wastes in Qatar is provided in **Table 3**.

Table 3. Typical characteristics of the wastes in Qatar.

S.no	Date seeds	Cattle manure	Sheep manure	Goat manure	Horse manure	Camel manure	Poultry litter	Food waste	Wastepaper	Textile waste	Waste tyre	Wastewater sludge
Moisture content (wt. %)	As received-basis	As received-basis	As received-basis	As received-basis	As received-basis	As received-basis	As received-basis	As received-basis	As received-basis	As received-basis		As received-basis
Moisture	10.20	85.12	47.80	37.61	55.00	38.00	26.00	77.20	24.00	10.00		10.50
Proximate analysis (%)	Air dried-basis	Air-Dried-basis	Air Dried-basis	Air Dried-basis	Air dried-basis	Air dried-basis	Air-dried	Air-dried-basis		Air-dried basis	As-received	Air-dried-basis
Moisture	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	0.50	8.00
Volatile matter	67.91	63.95	59.98	65.65	70.55	60.95	60.33	61.50	76.82	82.99	56.40	51.46
Fixed carbon	20.35	13.90	12.79	15.64	10.93	11.53	16.24	22.80	9.29	0.79	27.10	5.95
Ash	3.74	14.15	19.23	10.71	10.52	19.52	15.43	7.70	5.89	8.22	16.00	34.59
Ultimate analysis (%)	Dry-basis	Dry-basis	Dry-basis	Dry-basis	Dry-basis	Dry-basis	Dry-basis	Dry-basis	Dry-basis	Dry-basis	Dry-basis	Dry-basis
Carbon	44.42	34.80	40.59	33.44	38.35	27.83	40.00	43.71	43.00	41.40	71.33	25.27
Hydrogen	6.42	4.98	5.10	5.03	5.23	1.02	5.40	6.96	6.00	5.90	4.62	2.81
Nitrogen	0.79	2.28	2.10	1.94	0.80	2.17	5.60	3.57	0.36	1.10	0.18	3.42
Oxygen	44.29	42.25	30.70	47.95	43.48	47.75	33.50	36.48	43.80	42.30	6.78	30.27
Sulphur	0.00	0.31	0.61	0.00	0.71	0.00	0.10	0.09	0.17	0.40	1.01	0.63
Chlorine	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.82	0.17	0.00	0.00	0.00
Ash	4.07	15.38	20.90	11.64	11.44	21.23	15.40	8.37	6.50	8.90	16.08	37.60
HHV	16.98	13.33	8.36	12.37	14.87	4.18	16.00	19.10	17.43	21.80	31.22	13.64
Reference	[30]	[31]	[32]	[33]	[34]	[30]	[35]	[36]	[37]	[38]	[39]	[40]

Date seed has a high fixed carbon (20%) and volatile (68%) content, but very little ash (4%). It has a high elemental carbon content (44%) as well as a high oxygen and hydrogen content (50%). It does, however, have a very low nitrogen composition (1%), implying that the NO_x emission from pyrolytic degradation would be negligible. The absence of sulphur and chlorine indicates that no SO_x or chlorine gas will be released during its decomposition [41,42].

All of the manure samples have a high volatile content (60-70%) but a moderate fixed carbon content (10-16%). Manure samples from cattle, sheep, camels, and poultry litter have a high ash content (14-20%), whereas goat and horse manure have a medium ash composition (11%). Cattle, sheep, goat, horse, and poultry litter have a moderate elemental carbon content (33-41%), but camel manure has a low carbon content (28%). Cattle, goat, horse, and camel manure have a high hydrogen and oxygen content (47-53%), whereas sheep and poultry litter have a low hydrogen and oxygen content (39%). Aside from horse manure, all manures contain significant amounts of nitrogen, particularly poultry litter, which is harmful because it can result in the release of significant amounts of NO_x emissions. Goat and camel manure samples contain no sulphur, whereas other manure samples contain traces of sulphur, so caution should be exercised when pyrolysing these samples. All of the samples have zero chlorine presence, indicating that no chlorine gas will be emitted during thermal degradation [43].

Wastepaper (77%) and textile waste (83%) have very high volatile content among municipal waste samples, while food waste has a relatively higher volatile content (62%). Waste tyres (56%) and wastewater sludge (51%), on the other hand, have a moderate volatile composition. Food waste (23%) and waste tyres (27%), on the other hand, have a very high fixed carbon content, whereas wastepaper has a moderate fixed carbon content (9%). However, the fixed carbon content of textile waste (1%), and sludge (6%), is extremely low. Food waste (8%),

wastepaper (6%), and textile waste (8%) have low ash contents, waste tyres have a high ash content (16%), and sludge has a very high ash content (35%). Municipal waste samples with high elemental carbon content include food waste (44%), wastepaper (43%), and textile waste (41%). Waste tyres have a high elemental carbon composition (71%), whereas sludge has a low carbon content (25%). Food waste, wastepaper, and textile waste have a high hydrogen and oxygen content (40-50%), whereas sludge has a low hydrogen and oxygen content (33%). The hydrogen and oxygen content of a waste tyre sample is very low (11%). Because food waste and sludge contain a significant amount of nitrogen, a significant amount of NO_x emissions can be expected. The other samples, wastepaper, textile waste, and waste tyre, contain only trace amounts of nitrogen and thus do not pose a threat to NO_x emissions. Because all of the municipal waste samples contain traces of sulphur, SO_x emissions from these wastes are to be expected when they decompose. Only food waste and wastepaper show the presence of chlorine among the municipal waste samples studied, so extra precautions must be taken when thermally valorising the two wastes.

According to the discussion above, among the samples considered, date seed, sheep manure, camel manure, food waste, waste tyre, and sludge may favour more biochar production. The samples, particularly the date seed and waste tyre, may aid in the production of high-quality biochar. Although samples such as food waste, sheep manure, waste tyres, and sludge may have a high potential for biochar production, they must be thermally valorised safely because they contain hazardous substances. For example, sheep manure contains sulphur, food waste contains sulphur and chlorine, tyre contains sulphur, and sludge contains high levels of nitrogen and heavy metals.

3. Techno-economic analysis-modeling

An empirical process simulation model for waste pyrolysis is illustrated in **Figure 3**. During the development of the prediction model, the following assumptions were made [44].

- (i) Waste samples are decomposed/pyrolysed in an isothermal reactor operating in an N₂ environment;
- (ii) During the initial drying phase of the reaction, samples are pyrolysed and transformed into water, volatile gases (bio-oil), syngas (H₂, CO, CH₄, and CO₂), biochar, and ash;
- (iii) As specified in **Equations 1–3**, the products are synthesised during the first-stage of pyrolysis [45];
- (iv) In the next stage, as temperature increases, the bio-oil is further cracked into syngas.
- (v) During this phase, the synthesised gas products cracks into various gaseous components depending on the composition of the biomass.

$$\text{Bio – oil yield} = Y_{tar,F} + Y_{H_2O,F} + \text{Moisture content of samples} \quad (1)$$

$$\text{Pyrogas yield} = Y_{H_2,F} + Y_{CO,F} + Y_{CH_4,F} + Y_{CO_2,F} \quad (2)$$

$$\text{Biochar yield} = 0.106 + 2.43 * \exp (-0.66 * T * 10^{-2}) \quad (3)$$

Where Y denotes yield of a component in kg, while F denotes fuel undergoing the pyrolysis reaction, and T denotes temperature (°C). The bio-oil, pyrogas, and biochar yields are expressed in kg/kg of biomass.

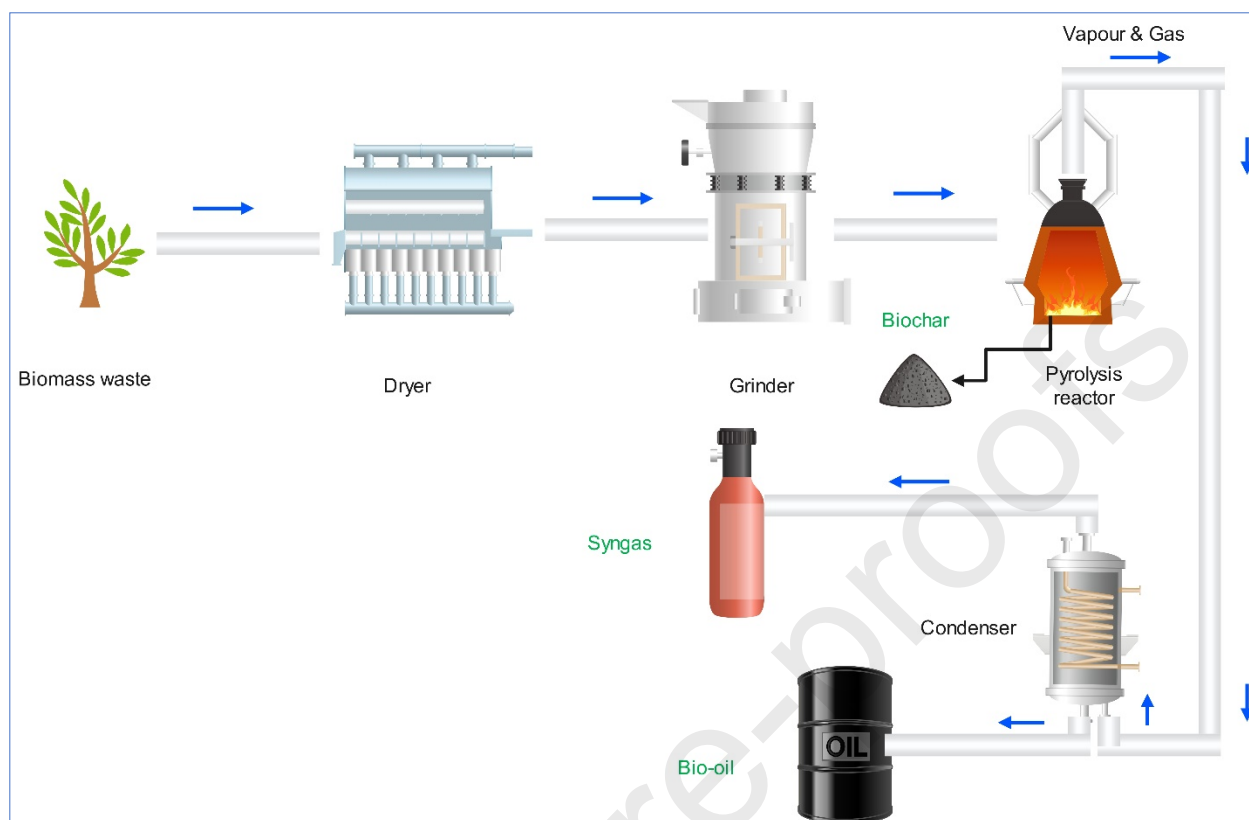


Figure 3. A streamlined flow diagram of the waste pyrolysis process.

The empirical model was initially developed by Neves *et al.* [44]. Multiple reactor sets were used to test pyrolysis in a wide range of temperatures (between 200 and 1000°C) on over 60 different types of biomass wastes. After the data were collected and structured, they were analysed to gain a better understanding of the pyrolytic process. Bio-oil, syngas, biochar, and water are the products of biomass pyrolysis, and from their characteristics (elemental compositions and energy contents), empirical relationships for pyrolysis stoichiometry can be derived. Cheng *et al.*'s model [46] was used to estimate energy requirements for the system, and Dulong's formula [47] was used to calculate energy content.

The equations that have been previously reported are used to determine the economic parameters, which are provided as a supplementary file. **Table 4.** lists the presumptions used for the economic assessment [48].

Table 4. Economic assessment assumptions.

Parameters	Values
Plant lifespan	25 years
Discount rate	20%
Annual operating hours	8,000 h/y
Transportation distance	100 km
Analysis year	2021
Plant's location	State of Qatar
Waste	10-100 USD/T
N ₂ gas	0.15 USD/kg
Water	1.479 USD/m ³
Electricity	0.035 USD/kwh
Biochar	0.2 USD/kg
Bio-oil	0.4 USD/kg
Syngas	0.056 USD/kg
Natural gas	2.545 USD/mmbtu
Ash disposal	16.3 USD/T
Wastewater discharge	0.27 USD/T
Operating temperature	250/500°C
Drying efficiency (%)	90%
Nitrogen flow rate	5 litre/min. T
Reaction time	30 min

A plant lifespan of 25 years was assumed based on the data reported elsewhere [49]. It is assumed that the plant operates for 8000 hours per year, taking into account a one-month period dedicated to annual maintenance. The study considered a transit distance of 100 km, taking into account the geographical characteristics of Qatar. Given that the proposed facility is intended to be situated in a central location within the country, a distance of 100 kilometres is deemed adequate for the transportation of waste from any region within the country. Dateseed waste feedstock is assumed to have a price of 100 USD/T, while food waste feedstock and wastetyre are assumed to have a price of 10 and 80 100 USD/T, respectively. Other waste feedstocks are assumed to cost 30 USD/T. The primary decomposition of pyrolysis, which is accountable for the generation of biochar, typically occurs within the temperature range of 250 to 500°C. Therefore, only these specific temperatures are considered in this current investigation.

3.1. Sensitivity analysis

Sensitivity analysis is the study of how the uncertainty in a process's output can be assigned to various sources of uncertainty in its inputs. A temperature sensitivity analysis of the effect of slow and fast pyrolysis on pyrolysis product outputs and syngas composition is discussed further below.

3.1.1. Product distribution

The influence of temperature on the output of bio-oil, biochar, and syngas is presented in **Table 5**. In all feedstocks, the yield of biochar decreased as temperature increased from 250 to 500°C. However, the increase in temperature generated more bio-oil and syngas yields. The production of biochar decreases with increasing temperature as a result of carbon's reaction with other elements to produce lighter gas and liquid hydrocarbon. The increase in the production of bio-oil and syngas is attributed to the breakdown of single C-H and double C-H, which produces more volatile and lighter products. The reaction of C with H and O also boosted the synthesis of bio-oil and syngas [50].

Table 5. Effect of temperature (250°C and 500°C) on pyrolysis products yield.

Feedstock	Bio-oil		Biochar		Syngas	
	250°C	500°C	250°C	500°C	250°C	500°C
Date seeds	19.40	43.20	49.80	17.08	1.07	9.93
Cattle manure	7.07	31.95	43.44	14.80	8.77	13.26
Sheep manure	28.88	39.43	29.72	13.95	0.32	6.15
Goat manure	6.76	27.85	35.17	15.48	15.13	17.35
Horse manure	10.32	35.27	45.65	15.58	8.37	13.42
Camel manure	0.00	0.70	23.56	10.77	52.24	55.27
Poultry litter	27.62	40.27	32.96	14.70	0.15	6.78
Food waste	42.29	47.28	22.37	14.27	0.05	5.73
Wastepaper	17.18	41.07	48.48	16.61	3.38	11.03
Textile waste	16.93	39.99	47.05	16.12	2.49	10.26
Waste tyre	48.90	65.24	34.87	14.00	0.00	1.48

Wastewater sludge	1.80	20.98	30.90	10.52	13.43	13.47
Multi-feed	24.97	41.59	39.08	15.72	0.11	7.87

In the case of date seed, increasing the temperature from 250 to 500°C increased bio-oil production from 19.40% to 43.33%. Bharath *et al.* also stated that increasing the temperature for date waste pyrolysis from 300 to 500°C led to an increase in bio-oil yield from 12.0 to 66.5% [51]. Biochar production, on the other hand, is found to be maximum (49.80%) at the lowest pyrolysis temperature (250°C). Among all the feedstocks considered, date seed contributed the highest biochar production (50% at 250°C and 17% at 500°C), which can be attributed to its high carbon content.

The composition of manure of different animals varies very widely especially C, O, and volatile content which eventually affects the composition of pyrolysis products with pyrolysis conditions. Maximum biochar production (at 250°C) is found to be 45.65% and 43.43% for horse and cattle manure, respectively. Higher biochar production is due to higher carbon and fixed carbon. Increase in temperature produced an increase in the bio-oil yield of cattle (7.07 to 31.94%) and horse (8.77 to 13.26%) manure. The rise in temperature also increased the syngas yield of cattle (10.32 to 35.26%) and horse (8.36-13.41%) manure. Atienza-Martinez *et al.* observed a similar behavior of pyrolytic products (biochar, bio-oil, and syngas) in cattle manure [52]. By raising the temperature from 250 to 500°C, the biochar yield in sheep and goat manures is reduced by 17% and 20%, respectively. Due to the higher volatile content and oxygen content of goat manure, the syngas yield is almost 10 to 15% higher for goat manure than for sheep manure at both temperatures. Poultry waste produces as much biochar, biooil, and syngas as goat and sheep manure. In the case of camel manure, the syngas yield is greater than 52% at both 250 and 500°C, making it a significant pyrolytic product of camel manure pyrolysis. Bio-oil, on the other hand, is

almost non-existent at both temperatures, whereas biochar yield ranges from 10 to 23%. The increased syngas production is due to the catalytic effect of Fe, Al, Mg, and K present in ash.

In the case of wastewater sludge, temperature increase (250 to 500°C) decreased biochar yield from 30.89 to 10.20% while bio-oil yield increased from 1.8% to 20.89%. The composition of syngas does not change significantly with temperature and remains close to 15%, which is attributed to extremely low C content and low oxygen content. Food waste pyrolysis produced the highest yield of bio-oil (47% at 500°C). The biochar yield decreased from 22.37 to 14.26% when the temperature was raised from 250 to 500° C. The yield of syngas is negligible, with a maximum of 5% observed at 500°C. When the temperature was raised from 250 to 500°C for waste tires, the yield of biochar decreased (from 34 to 14%) while the yield of biooil increased (from 48 to 65%). No appreciable syngas yield is produced at either temperatures. At 250°C, wastepaper and textile produced a high biochar yield of 48.48% and 47.04%, respectively. When the temperature was raised, both feedstocks produced 8% more syngas. The high cellulosic content of paper and textile waste accounts for their pyrolytic behavior.

Blending different feedstock is an effective way to get the desired output while avoiding the cost of waste sorting. According to the figures, at 250°C, the obtained biochar and bio-oil yields are 39.07% and 24.96%, respectively, while at 500°C, the obtained biochar and bio-oil yields are 15.71% and 41.58%, respectively. At 500°C, the syngas yield is found to be highest (8%).

3.1.2. Syngas composition

Syngas is a part of pyrolysis products. The utilization of syngas for various applications and as a fuel is based on the composition of gases in syngas and the heating value of produced gas. The syngas gas composition and heating value of syngas obtained is illustrated in **Figure 4**.

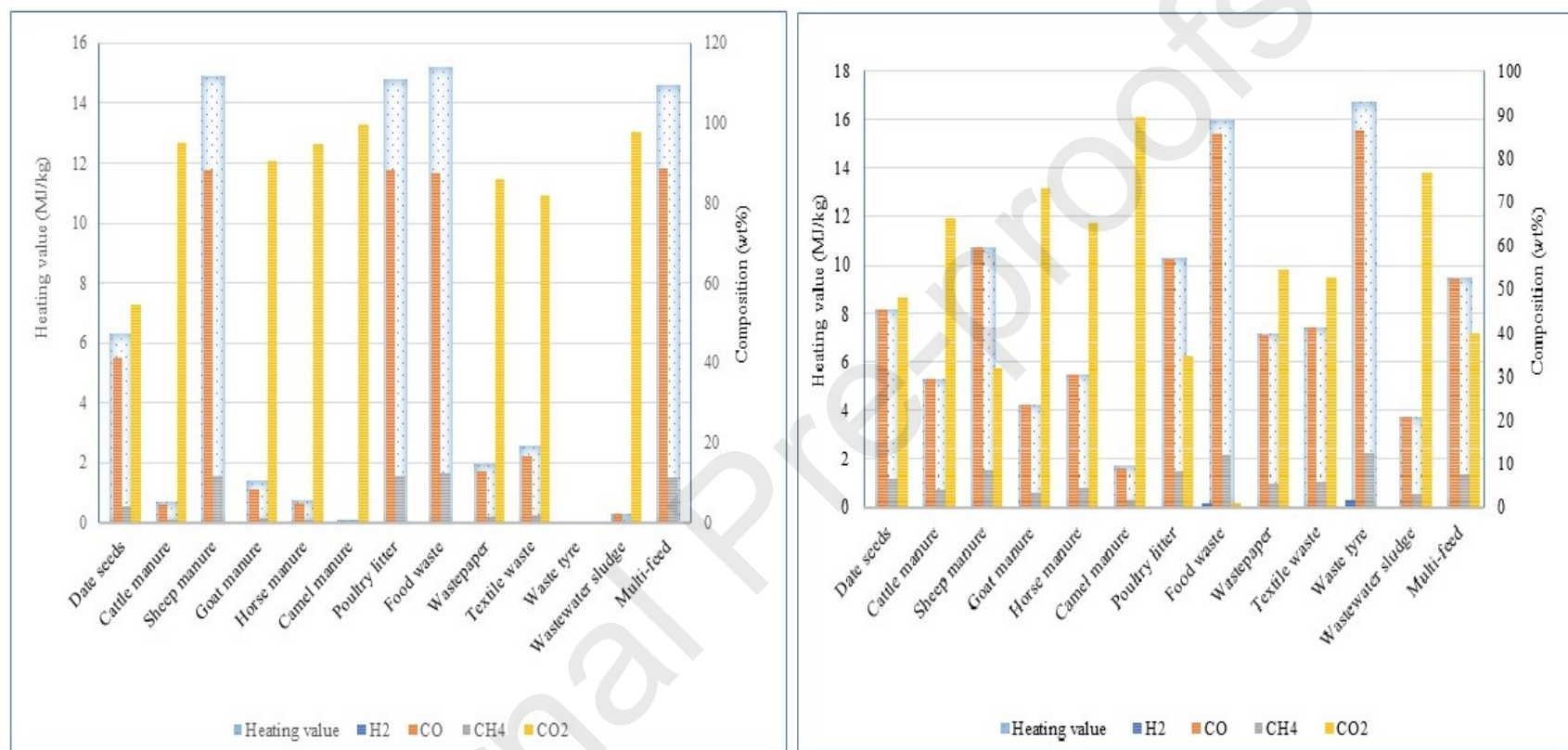


Figure 4. Syngas composition and heating values at 250°C and 500°C.

Figure 4. illustrates that CO and CO₂ constitute the majority of syngas, with a maximum composition of 90%. When the temperature rises, the CO₂ composition significantly declines while the CO composition responds in a variable way. The higher CO and CO₂ compositions at lower temperatures are due to combustion reactions, which allow for more CO and CO₂ production. The higher CO content at higher temperatures is due to the Boudouard reaction, as many researchers have reported [53,54]. The H₂ and CH₄ content, on the other hand, is extremely low, with a maximum composition of less than 10%. This is due to the fact that the process takes place at a lower temperature in the absence of an oxidizing agent. However, there is a slight increase in H₂ and CH₄ compositions as the temperature rises from 250 to 500°C. The methane forming reaction, and, in some cases, the water gas-shift reaction cause the enrichment of H₂ and CH₄ content.

Even at 500°C, date seed has a very moderate syngas composition, with H₂-0.31%, CO-45.08%, CH₄-6.39%, and CO₂-48.21%, respectively. The heating value increases with temperature from 6.29 to 8.137 MJ/kg due to increased methane content, which has a higher heating value than CO and CO₂. At 250 and 500°C, the heating value of syngas produced by pyrolysis of camel manure is extremely low, measuring only 0.060 and 1.73 MJ/kg, respectively. This is because of the higher CO₂ content, which ranges from 89.62 to 99.56%. In comparison to H₂ and CH₄, CO₂ content is extremely low. The heating value of cattle manure increases from 0.66 to 5.28 MJ/kg. This is due to a decrease in CO₂ content from 95.18 to 66.37% and a significant increase in other gases such as CO, CH₄, and H₂ as temperature increases.

The heating value of sheep manure was higher at 250°C (14.88 MJ/kg) than at 500°C (10.73 MJ/kg). This low value at higher temperatures (500°C) is due to a decrease in CH₄ content from 11.84 to 8.41%, which can be attributed to an increase in CO₂ composition and CO content. Similar profiling of syngas composition and heating values is observed in poultry litter. In contrast,

the heating value of paper and textile waste increases from 1.93 to 7.13 MJ/kg and from 2.54 to 7.44 MJ/kg as the temperature rises from 250 to 500°C. This results from a decrease in the compositions of CO and CO₂, as well as an increase in the content of CH₄.

Due to the higher content of CH₄ (around 12%), food waste exhibits higher heating values of 15.23 and 15.89 MJ/kg at 250 and 500°C. Variations in the gas composition cause the heating value of the multi-feed or blend to drop from 14.60 to 9.42 MJ/kg during pyrolysis. The dry reforming of methane at higher temperatures is what causes the reduction in CH₄.

3.2. Economic analysis-outcomes

A detailed economic analysis is conducted to evaluate the revenue potential of biochar generation in Qatar. Seven scenarios are considered, where in six of the scenarios, a single-feed plant is developed with a maximum capacity equal to 50% of the available feedstock in the country. Whereas the last scenario assumes a Mega multi-feed plant (2.5 million T/y), with a blending ratio representing the actual feedstock distribution. The following sub-sections discuss in detail the outcomes of the economic analysis. The main economics parameters attained for slow and fast pyrolysis are illustrated in **Figures 5.** and **6.**, respectively. The parameters include the capital expenses (CAPEX), operating expenses (OPEX), sales, profit, and net present value (NPV).

Evidently, the plant capacity has played a vital role in the variation amongst the different scenarios. CAPEX and OPEX variations between slow and fast pyrolysis were minimal, whereas they widely varied based on feedstocks and capacities at 3.25–596 million USD for CAPEX, and 1.86–203 million USD/y for OPEX. Sales and profits have noticeably varied based on the type of pyrolysis. Where fast pyrolysis produced more bio-oil, which is associated with a higher market value as compared to biochar. In average, a 13% increment in sales is achieved when the plant is

operated at fast-pyrolysis mode. Considering the excessive cost and low availability of date pit feedstock, date pit-based plants were found to be unfeasible. Furthermore, camel manure and wastewater sludge were associated to negative profits, which is due to the low generation of bio-oil, in both slow and fast pyrolysis. Meanwhile, NPVs were negative for all plants capacities below 50 T/hr., given a discount rate of 10%.

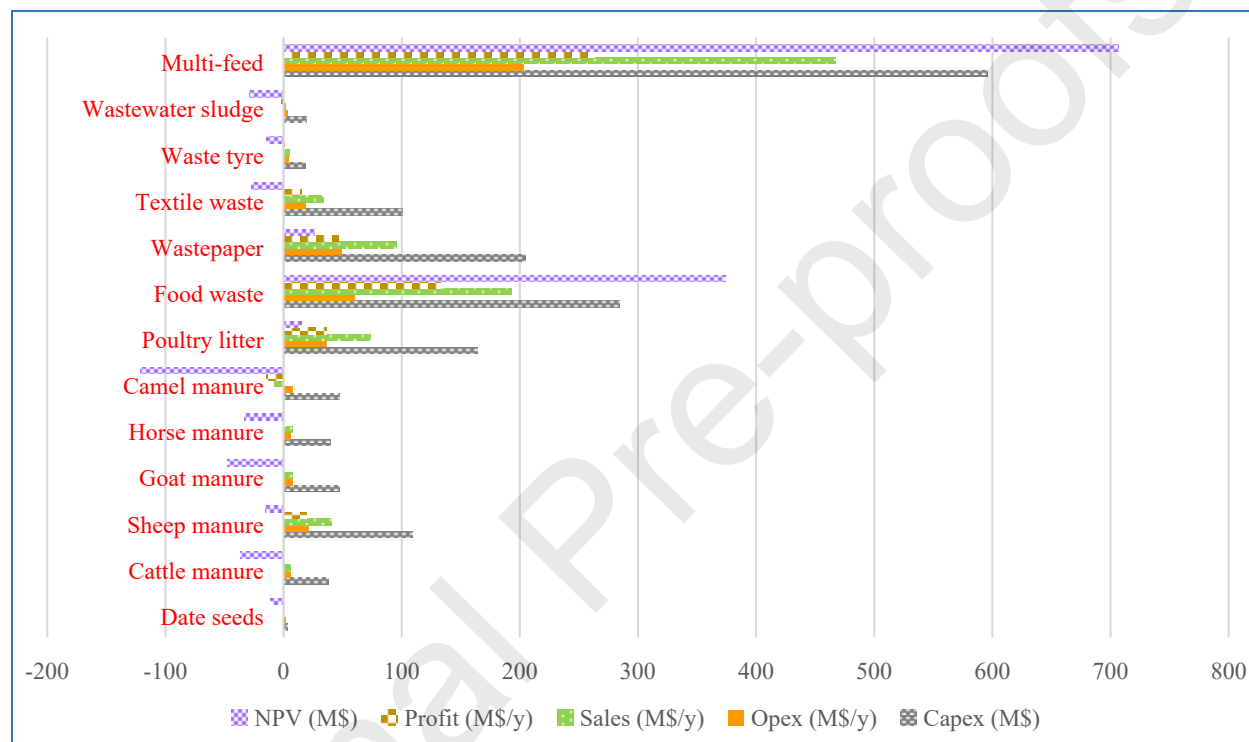


Figure 5. Economic parameters for slow pyrolysis plants (at 250°C).

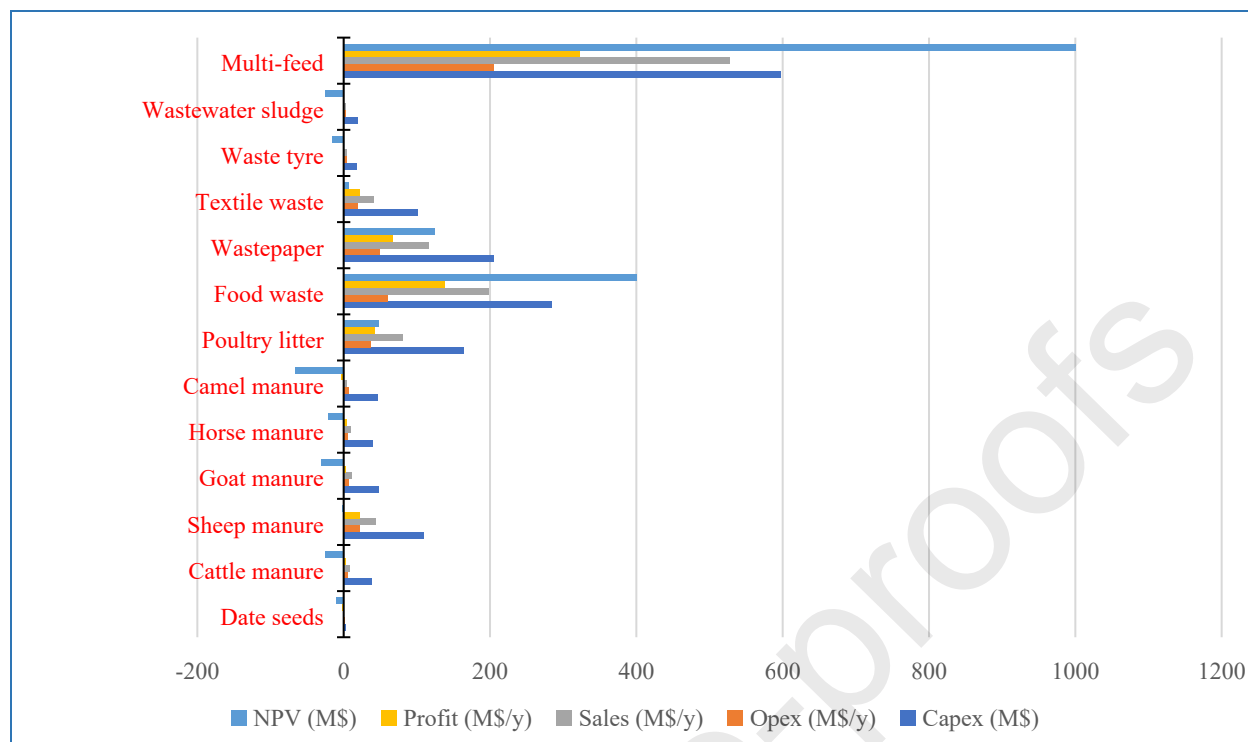


Figure 6. Economic parameters for fast pyrolysis plants (at 500°C).

To detail the CAPEX parameter, a breakdown is illustrated in **Figure 7.** for the multi-feed plant. The breakdown is the same for all scenarios. Where the purchased equipment dominated the CAPEX and occupied ~35%, followed by the construction expenses, engineering costs, and service facilities at around 8-9% each.

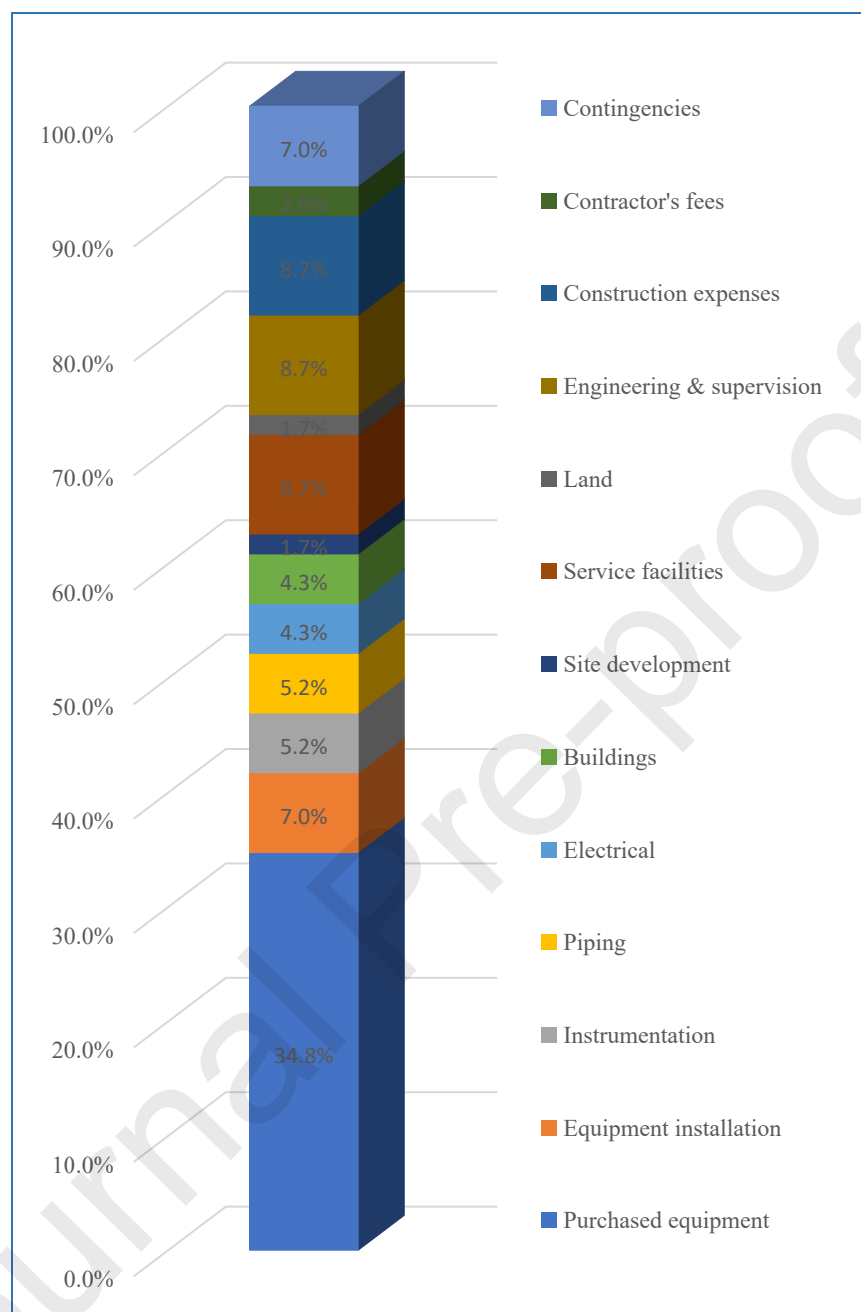


Figure 7. Breakdown of CAPEX for multi-feed plant.

In addition, the breakdown of multi-feed plant's OPEX is illustrated in **Figure 8a.** and **8b.** for slow and fast pyrolysis, respectively. Raw materials (*i.e.*, nitrogen gas) occupied almost one third of the OPEX (33.8–34.1%), while feedstock occupied ~30% of OPEX for both pyrolysis types. The third highest OPEX components were the utilities at 15.3-15.4% of total OPEX. Due to higher energy requirements, the fast-pyrolysis mode resulted in slightly higher OPEX.

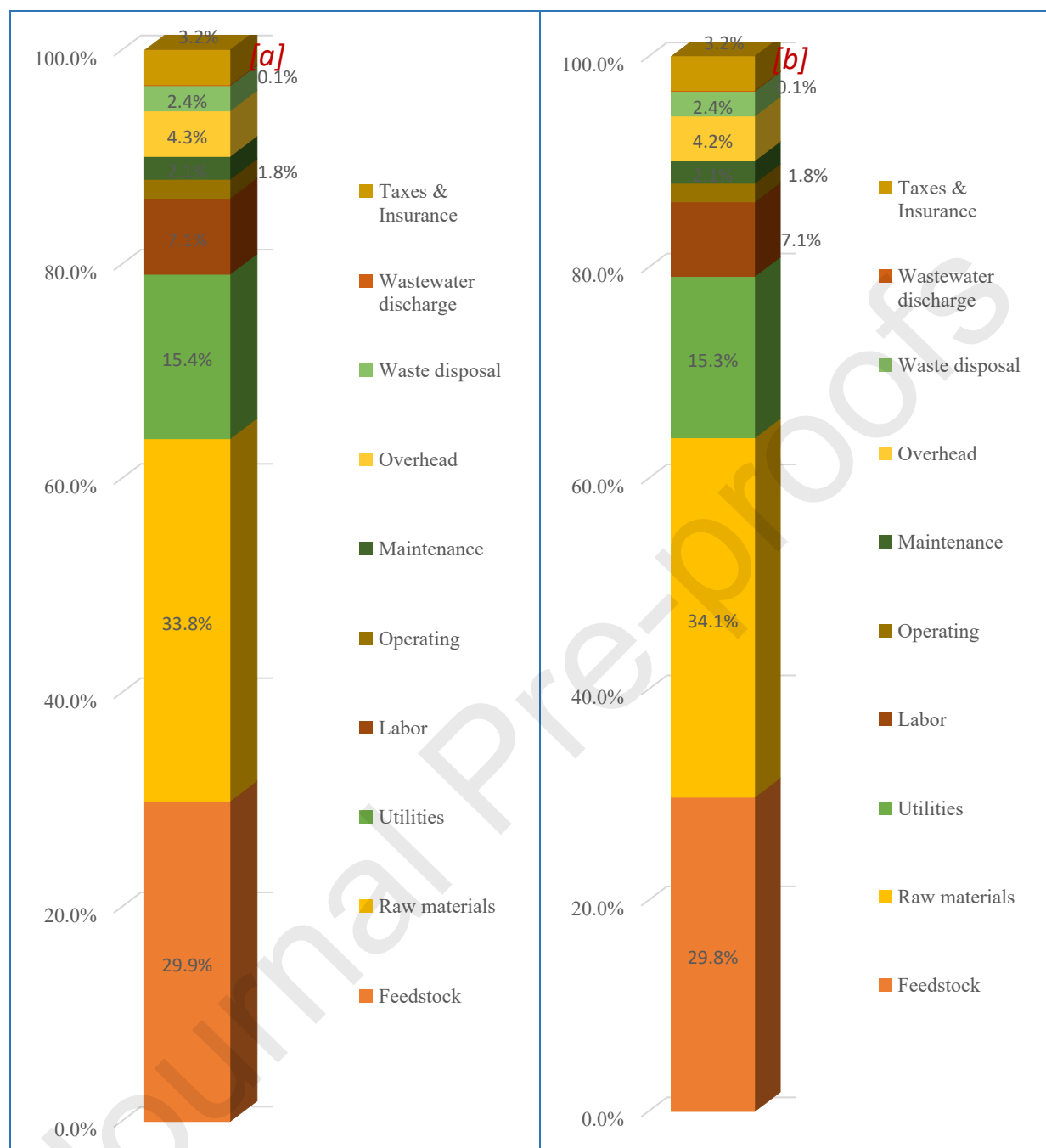


Figure 8. Breakdown of multi-feed plant's OPEX for [a] slow pyrolysis, and [b] fast pyrolysis.

3.2.1. Return on investment

One of the most crucial economic criteria for investors is the return on investment (ROI), where it shows the projected annual return as a share of the project investment [55]. Three feedstocks (date pits, camel manure, and wastewater sludge) were linked to negative ROIs across

the various scenarios as a result of limited plant capacities, as shown in **Figure 9**. For single feedstock plants, food waste is linked to the highest ROI at 47 and 49% for slow and fast pyrolysis, respectively. While the highest overall ROI is achieved for a multi-feed plant operated at fast-pyrolysis mode, achieving an ROI of 54%.

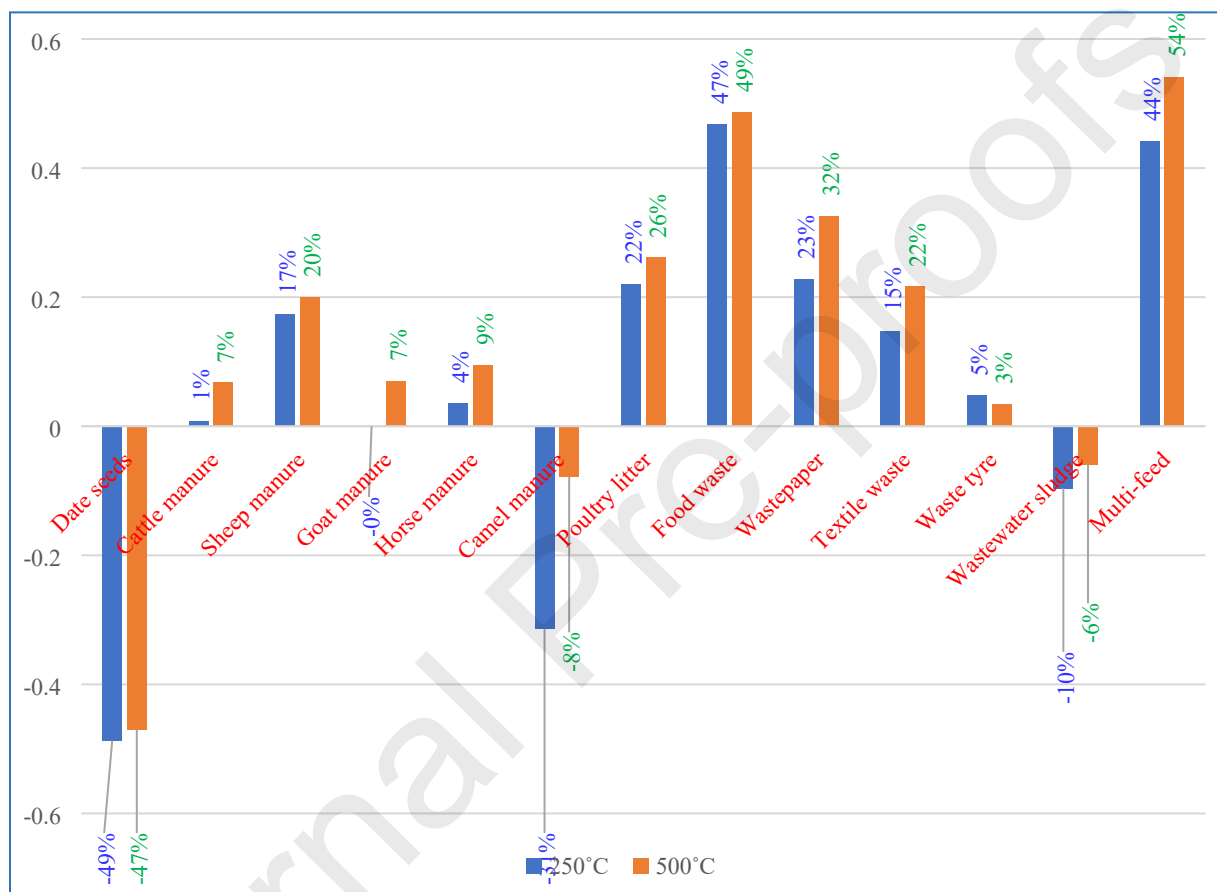


Figure 9. ROI (%) for different feedstocks and operating modes.

3.2.2. Payback period

The timeframe for CAPEX payback is illustrated in **Figure 10**. for different feedstocks and operating mode scenarios. The payback period is highly dependent on net cash flow (profit), as well as the project investment (CAPEX) [56]. Obviously, all scenarios that achieved negative profits were not able to pay back the CAPEX (including plants operating based on date pits, camel manure, and wastewater sludge). Other scenarios, such as the fast pyrolysis of waste tires

and the slow pyrolysis of cow, goat, and horse manures, both produced low profits but were unable to cover the costs of the project within the 25-year period. However, when food waste is used as a single feedstock, the shortest payback period for slow pyrolysis is achieved at 2.14 years, while a multi-feed plant achieved the overall shortest payback of 1.85 years when the plant is operated in fast-pyrolysis mode.

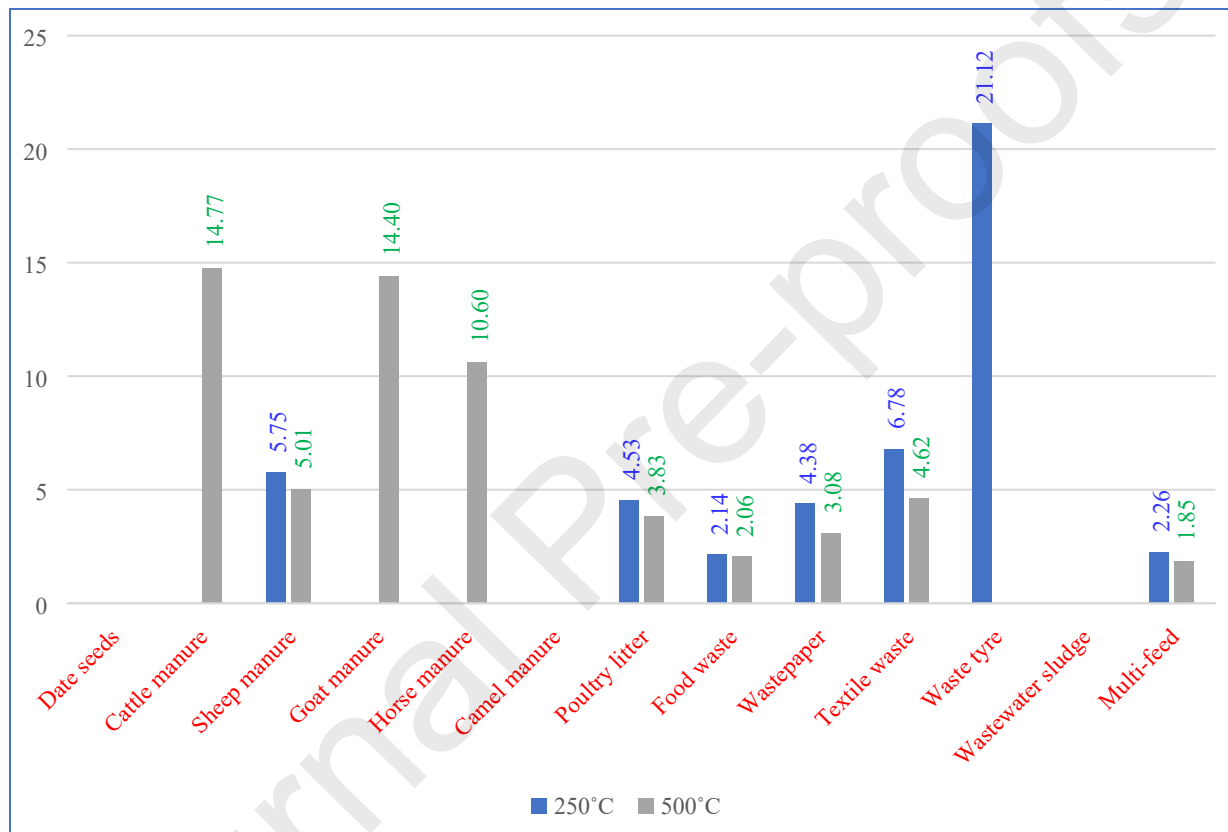


Figure 10. CAPEX payback period for different feedstocks and operating modes.

3.2.3. Minimum selling prices

The most important parameter for the commercialization of products is the minimum selling price (MSP), which is evaluated based on the levelized cost concept, considering the value of money over the lifespan of the project [57]. The attained biochar's MSPs are presented in **Figure 11**. For slow pyrolysis, where larger quantities of biochar are produced at the expense of bio-oil, only three single feedstocks attained an MSP below the market price of biochar (<0.2

USD/kg). These feedstocks included poultry litter, food waste and wastepaper. In addition, the multi-feed plant generated biochar at an MSP of as low as 0.06 USD/kg. While for fast pyrolysis, all feedstocks have achieved an enhanced MSP due to the production of bio-oil which can be sold at a higher market price (~0.4 USD/kg). While a negative MSP is achieved for some scenarios due to excessive production of bio-oil, whose sales alone can cover all annual costs. Therefore, selling biochar at any price is still profitable in the former scenarios. It can be concluded that operating the plants in fast pyrolysis mode helps achieve a better profitability at the expense of biochar yield. Hence, the selection of optimal biomass blend and an adequate operating condition are vital to realize a balance between biochar yield and its associated profit.

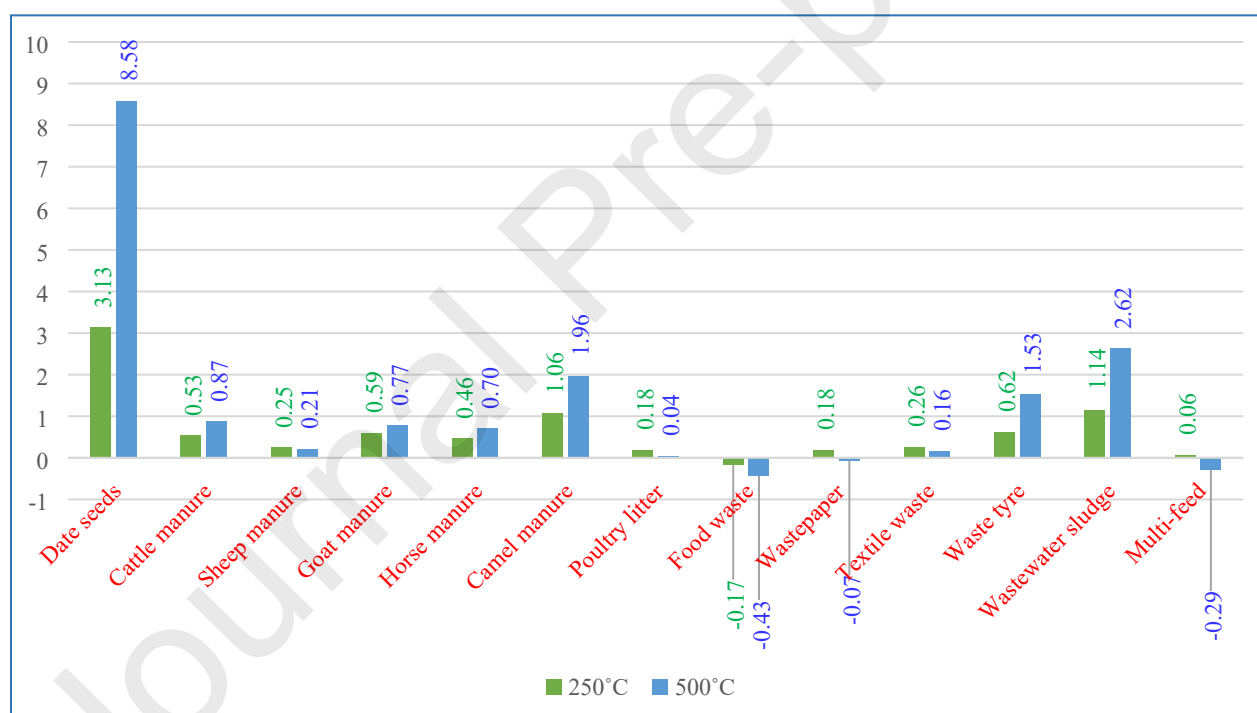


Figure 11. Biochar MSPs for different feedstocks and operating modes scenarios.

3.2.4. LCA results

A useful technique for calculating and contrasting the impact of human activity on the environment is to evaluate the "footprint" of a particular product. Footprints are "indicators of human pressure on the environment," which aid in understanding environmental changes and the

consequences of this pressure. Carbon footprints, energy footprints, water footprints, and land footprints are examples of common footprints [58]. The carbon footprint is calculated by adding all greenhouse gas emissions (direct and indirect) from a process and expressing it in terms of total CO₂ equivalence (mass). The amount of energy required for a process to produce a product is referred to as its energy footprint whereas water footprint refers to the amount of water required to produce a product over the entire supply chain. The land needed to produce a product or used by a plant or process is referred to as the land footprint. The outcome of the LCA is illustrated in **Figure 12**.

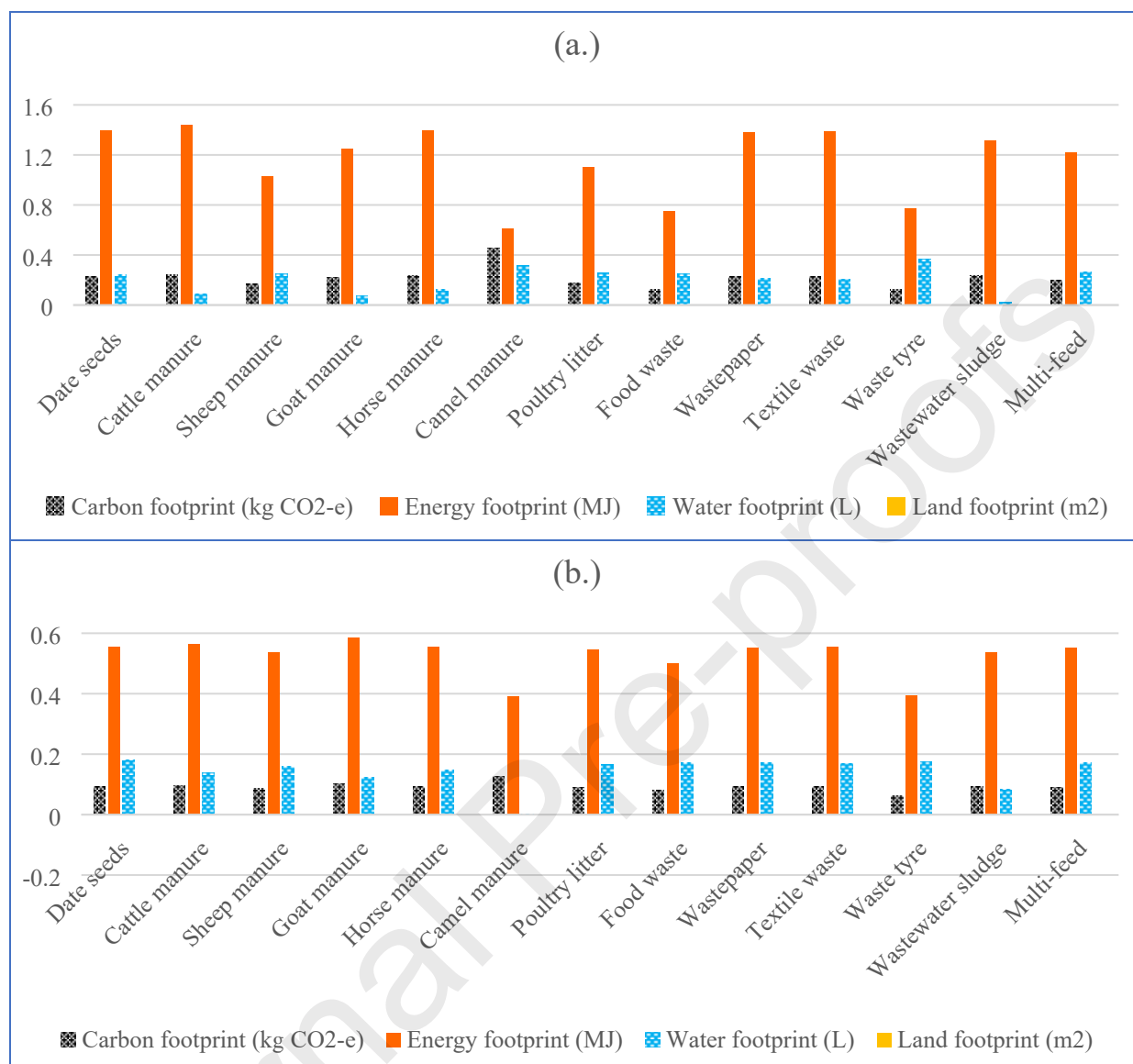


Figure 12. LCA results based on 1 kg of biochar production (a.) 250°C (b.) 500°C.

The highest carbon footprint was found in camel manure (0.45 kg CO_{2-e}) at 250°C, while the lowest was found in food waste (0.12 kg CO_{2-e}). Camel manure exhibited the highest carbon footprint (0.12 kg CO_{2-e}) even at 500°C, and waste tyres exhibited the lowest (0.06 kg CO_{2-e}). It is fascinating to note that all feedstocks had reduced carbon footprints at 500°C. Cattle manure had the highest energy footprint (1.44 MJ) at 250 °C, while camel manure had the lowest energy footprint (0.61 MJ). At 500°C, goat manure had the highest energy footprint (0.58 MJ), while camel manure had the lowest (0.38 MJ). All feedstocks showed a reduced energy footprint at a

higher temperature (500°C). In the 250°C environment, waste tyre's water footprint (0.36 L) was highest, while wastewater sludge's water footprint (0.02 L) was lowest. Date seeds demonstrated the highest water footprint (0.18 L) at 500°C, while camel manure displayed a negligible footprint.

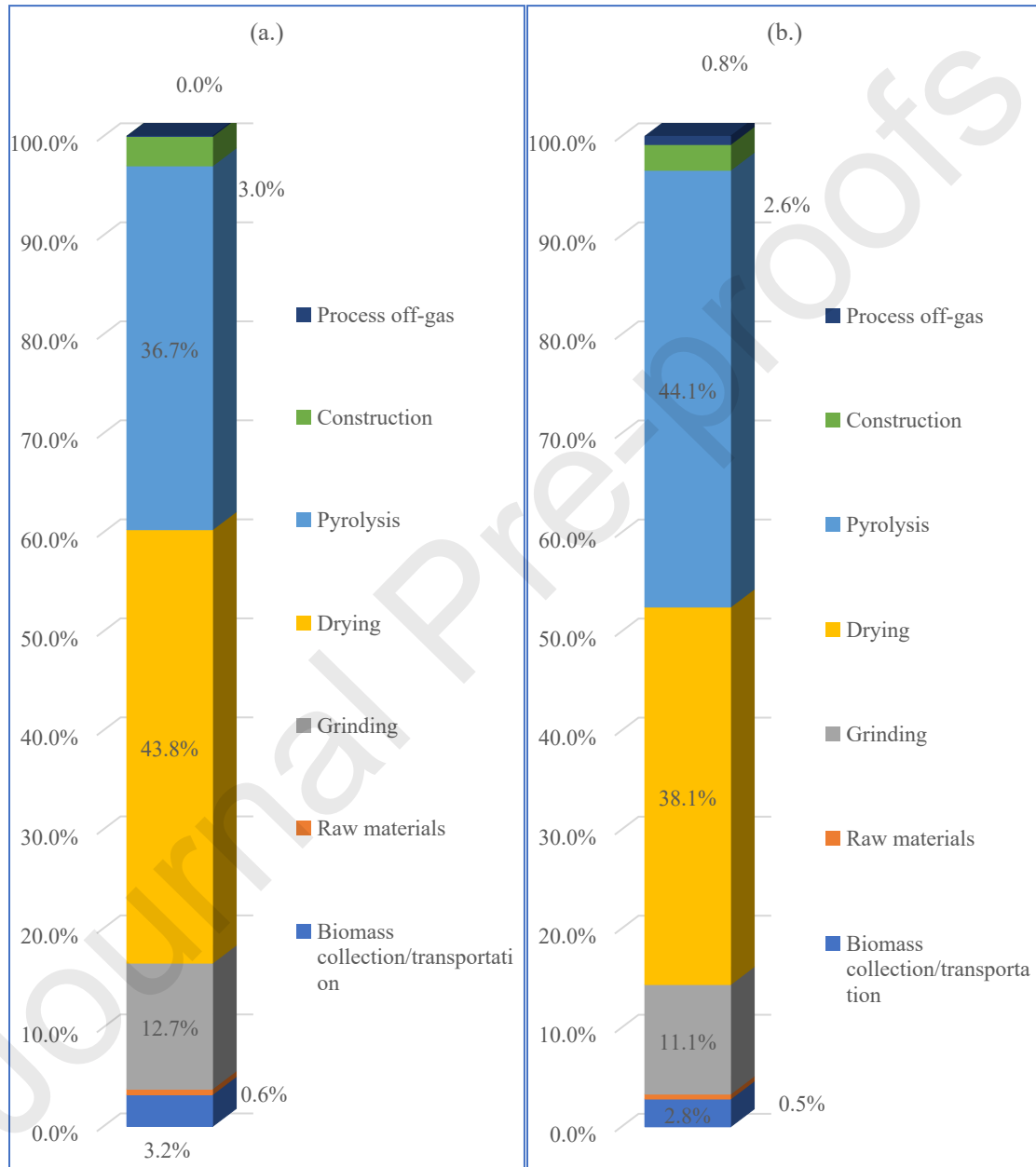


Figure 13. The breakdown of carbon footprint (a.) 250°C (b.) 500°C.

Figure 13. depicts the carbon footprint breakdown for the entire pyrolysis process. At the lower temperature (250°C), the drying step contributed the most (44%), followed by the pyrolysis

reactions (37%), whereas at the higher temperature (500°C), the pyrolysis reactions contributed the most (44%), followed by the drying step (38%). Other activities such as waste collection, raw material supply, grinding, and construction have nearly identical shares at both temperatures.

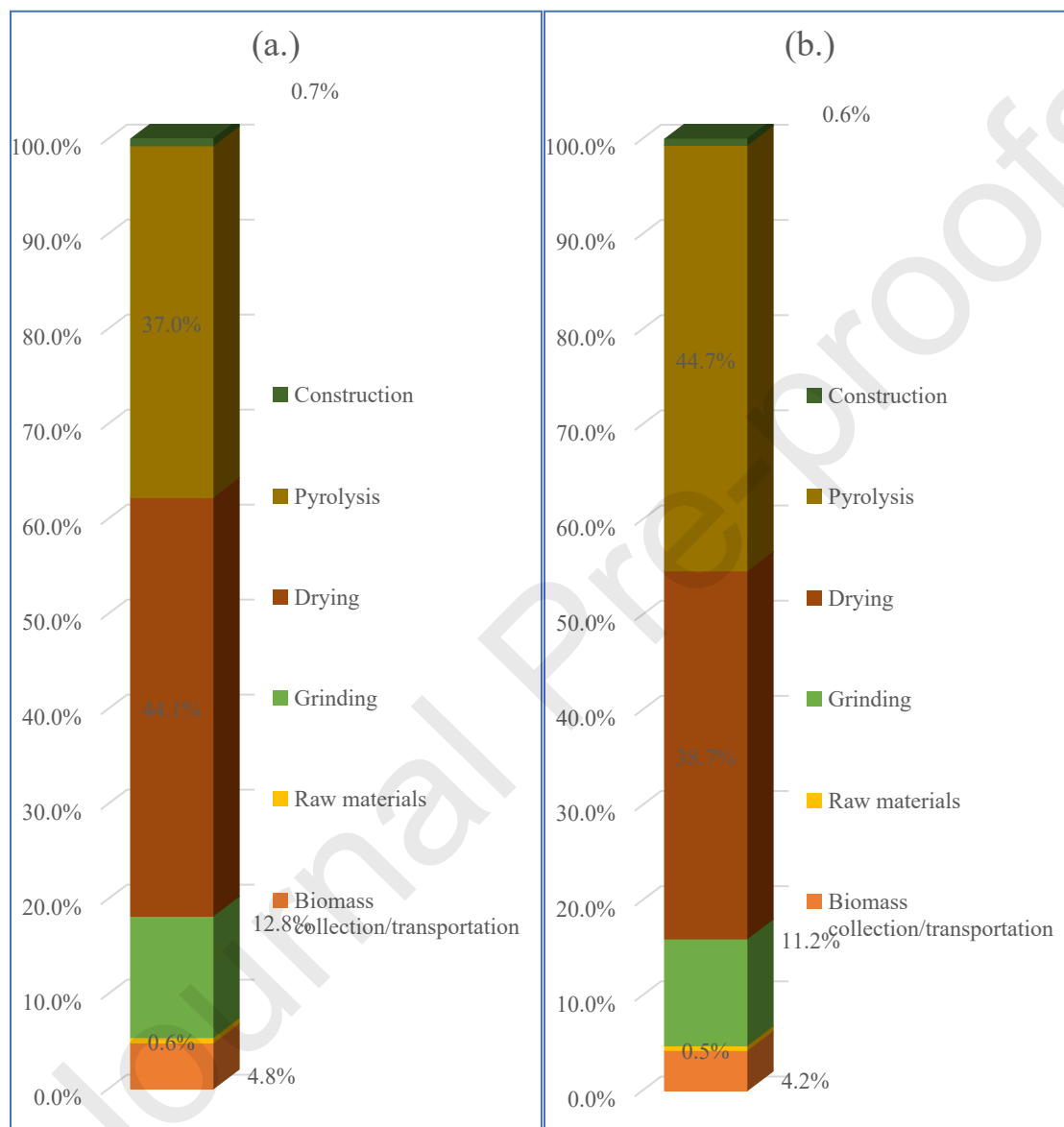


Figure 14. The breakdown of energy footprint (a.) 250°C (b.) 500°C.

The breakdown of the energy footprint for the entire pyrolysis process is shown in **Figure 14**. At the higher temperature (500°C), the pyrolysis reactions contributed the most (45%), followed by the drying step (39%), while at the lower temperature (250°C), the drying step

contributed the most (44%). Other activities like waste collection, obtaining raw materials, grinding, and construction have shares that are essentially the same at both temperatures.

4. Biochar generation and revenue potential from wastes available in Qatar

Table 6. shows the biochar generation and revenue potential from some of the most prominent wastes available in Qatar. The dry waste feed quantity is calculated assuming only 10% moisture suitable for pyrolysis treatment. Furthermore, the biochar yield is calculated using only two temperatures: 250°C and 500°C. Since most of the considered wastes are plant and animal biomass, this study arbitrarily chose a temperature of 250°C to pyrolyse the samples below 300-400°C, a temperature range where structural degradation occurs in cellulose and hemicellulose, whereas a temperature of 500°C was chosen to allow almost all volatiles to decompose. It should be noted that hemicellulose degrades thermally between 200 and 260°C, cellulose between 240 and 350°C, and lignin between 275 and 500°C [59,60]. The revenue potential of biochar is calculated using a biochar market price of 0.2 USD/kg.

Table 6. Biochar generation and revenue potential from the wastes available in Qatar.

S.no	Waste	Wet feed quantity (T/yr.)	Moisture content (wt. %) *	Dry feed quantity (T/yr.)	Biochar yield** (%) from the waste	Biochar yield (%) from the waste	Amount of biochar that can be generated from the waste (T/yr.)		Biochar annual revenue potential from the waste (Million USD)	
					at 250°C	at 500°C	at 250°C	at 500°C	at 250°C	at 500°C
1	Date pits	3,220	10.20	3,214	53.87	21.14	1,731	679	0.3	0.1
2	Cow dung	1,018,350	85.12	253,365	58.82	30.18	149,030	76,465	29.8	15.3
3	Sheep manure	462,200	47.80	287,488	50.62	34.85	145,522	100,183	29.1	20.0
4	Goat manure	143,070	37.61	103,568	46.81	27.13	48,478	28,094	9.7	5.6
5	Horse manure	114,080	55.00	62,744	57.09	27.02	35,820	16,953	7.2	3.4
6	Camel manure	142,975	38.00	102,942	44.77	31.98	46,092	32,924	9.2	6.6
7	Poultry litter	829,683	26.00	696,934	49.74	31.47	346,628	219,333	69.3	43.9
9	Food waste	1,799,670	77.20	590,292	30.74	22.64	181,456	133,630	36.3	26.7
10	Wastepaper	1,133,370	24.00	974,699	54.89	23.01	534,969	224,286	107.0	44.9
11	Textile waste	412,135	10.00	412,135	55.98	25.05	230,720	103,246	46.1	20.6
12	Wastewater sludge	40,959	10.50	40,754	50.95	30.09	20,764	12,261	4.2	2.5
13	Tires	36,496		36,496	68.50	48.12	24,998	17,560	5.0	3.5

* As-received basis

** comprising both biochar and ash

Wastepaper has the ability to produce the most biochar of any waste. For 250°C and 500°C, respectively, it is expected to produce 534,969 T and 224,286 T of biochar. Poultry litter, textile waste, food waste, cow dung, and sheep manure have all been found to produce a moderate amount of biochar. Food waste, despite its massive availability (1.8 MT), produces only a moderate amount of biochar due to its high moisture content (77%). Due to their limited availability, date pits among the wastes can produce the least biochar (3220 T).

Wastepaper has the greatest potential to generate income from biochar among the waste feeds. Its revenue potential is estimated to be 107 million USD per year for 250°C and 45 million USD per year for 500°C. The poultry litter has the second-highest potential for revenue after wastepaper (69 million USD per year for 250°C and 44 million USD per year for 500°C). Textile waste, food waste, cow dung, and sheep manure all have a reasonable potential for biochar revenue.

The estimated biochar yield and revenue potential are based on only-temperature (250°C and 500°C). Although pyrolysis temperature has a significant impact on biochar yield and quality, other factors such as feedstock type, feedstock size, reactor configuration, and pyrolysis residence time also have an impact on biochar yield and quality. High pyrolysis temperatures, in general, result in lower biochar yield, larger surface areas, higher ash contents, minimal total surface charge, higher water holding capacity, and higher pHs [61]. Furthermore, high temperatures increase the carbon content of biochar while decreasing the hydrogen and oxygen content. However, it is not necessary to conduct pyrolysis experiments (meant to produce biochar for soil amelioration application) at high temperatures because biochar obtained at low temperatures may perhaps meet the requirement for soil amendment and carbon sequestration. Consequently, it is

suggested that experiments involving pyrolysis for biochar production should start at lower temperatures.

5. Market intervention and carbon trading

In the current decade, a lot of work, effort and discussion is going on for developing energy trade based on the low-carbon energy system [62]. The market of bioenergy products and its derivative, both energy and material, is under development in parallel to fossil fuel-based products. According to various reports, biomass potential is about 200-700 EJ and is projected to be 50-1000 EJ in 2050 [63]. Biomass accounts for 10% of global energy supply and 13% of total energy consumption, equating to 50 EJ of biomass, with a potential range of 140-270 EJ [64]. The conversion of biomass or waste into biochar will not only result in a carbon neutral system but will also result in a negative carbon process due to the fixation of biochar as a component of bio energy. Tisserant *et al.* highlighted the trade-off benefits of biochar utilization in terms of energy products, mitigation potentials to fight climate change and its large spectrum of applications making a place in the world trading market [65]. In the future, bioenergy trade will be important because CO₂ emissions are approximately 2-9 kgCO₂/GJ.

Many market reports on the biochar sector's revenue and growth have been released in the last ten years, and it has enormous potential growth at the regional and global levels. These reports have projected that the biochar world market will have 13-17% of compound annual growth rate (CAGR) in between 2019 and 2024 due to its widespread application in food and energy sectors [66]. According to a recent publication, with effective marketing management and strategies, the biochar market can grow by 13.6% in terms of revenue and 11.2% in terms of volume between 2020 and 2028 [67]. These objectives can be met by making a preference intervention in the global

market through biochar trade stockholder engagement and, most importantly, fresh players in carbon trading or carbon pricing.

5.1. Stakeholder management for Market development

To develop a competitive bioenergy market, particularly for biochar, all system components must work together, engage, and intervene from research to commercialization. The five major components are researchers, supply chain, industry or investor, policy maker, and consumers. The effective relationship of the above-mentioned stakeholder can lead to the development of a circular economy of biochar that can push the fossil fuel boundary in terms of economy. For this purpose, researchers should have government and industry funding to develop more suitable products and technology. The feedback of end users will be a key in this scenario. In exchange, researchers should concentrate on developing biochar for various applications as requested by end users, which can produce equivalent or better alternative results [68]. The second most crucial component of this chain is investors or industries that are producing the product for the end users. They should invest in modern technologies and provide funding for research and a fund for marketing products. Policymakers both national (government) and international bodies, should introduce policies that will help the biochar economy in terms of facilitation for research and industry development, subsidy if needed, market campaigns and, most importantly, should be part of the future country policy. The end users should prefer to use biochar for a green ecosystem and provide honest feedback to producers. The supply chain is the thread between all stakeholders and the information flow medium that connects the market to research people. Thengan *et al.* related the stakeholder engagement for biochar economy as shown in **Figure 15.** below [69].

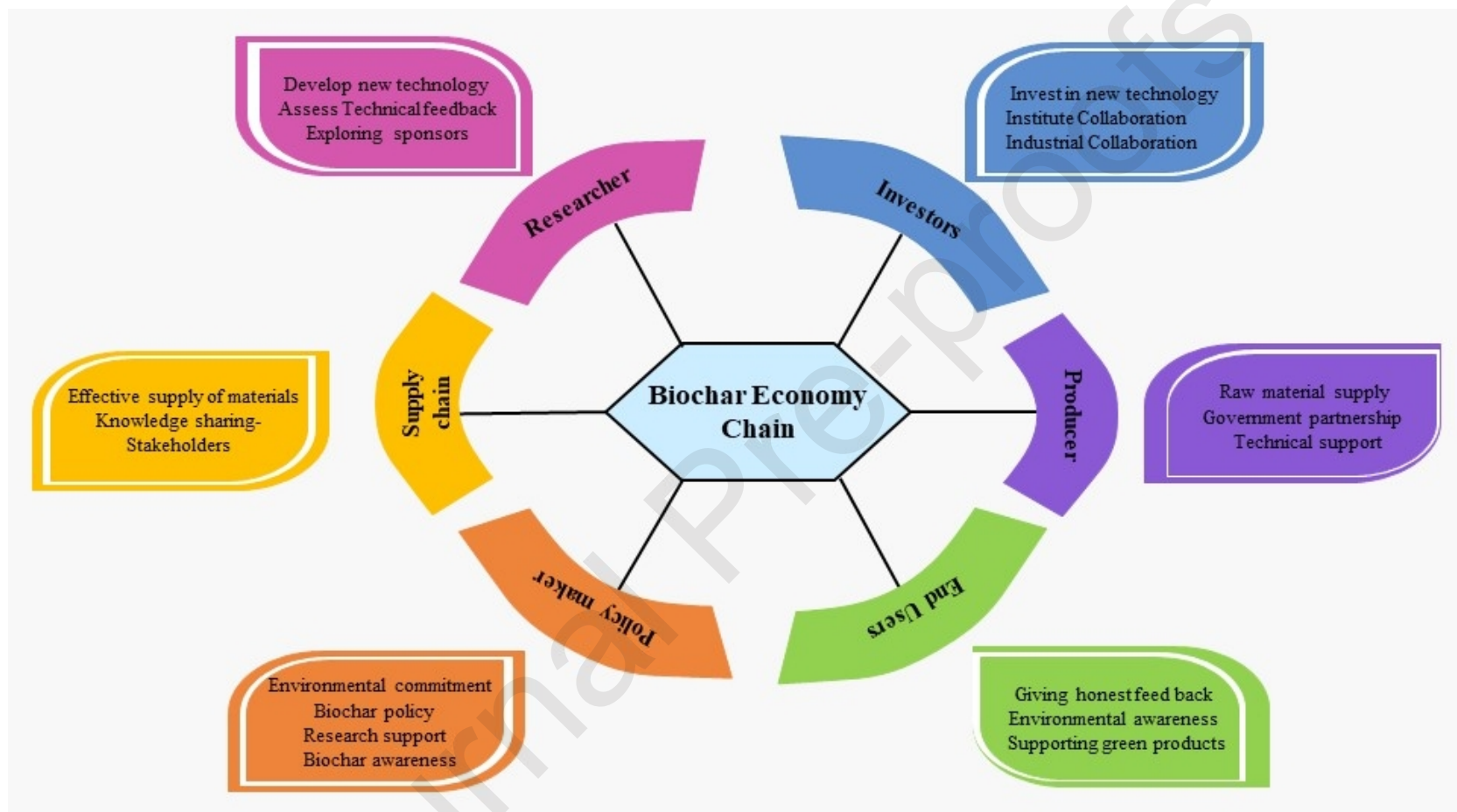


Figure 15. Circular marketing system for biochar economy.

5.2. Carbon Credit

Biochar has the potential to act as a carbon sink and may become the most important one if carbon credits for emissions offset are used. According to Matovic *et al.*, simply converting the 10% biomass into biochar with a 50% yield has an offset potential of 4.8 GtC/annum [70]. Tisserant and Cherubini reported that the total biochar CO₂ offset potential is 0.65 to 35 Gt CO₂eq/annual [65], and a latest study states that CDR potentials are 1.5–3.3 Gt CO₂eq/annual, by considering 50% and 67% residue of crop and forest.

Carbon trade is an amazingly effective and important device method to regulate CO₂ emission based on the carbon credit. In this system, a price has been given to a certain amount of emitted CO₂, and its buying and selling can be made [71]. To satisfy a CO₂ emissions balance, a party can buy the carbon credit from the other party that generates more emissions [72]. This could result in extremely healthy competition among biochar producers to use and produce more biochar. The global carbon credit trading market is extremely active, with the EU Emissions Trading System (EU ETS) accounting for 90% of all carbon trade. Many other important programs and bodies are also highly active, including the New Zealand Emissions Trading Scheme, the Tokyo Cap-and-Trade Program, California's Cap-and-Trade Program, the Regional Greenhouse Gas Initiative (RGGI) of the United States, *etc.*

Carbon pricing is particularly important and should be regulated by local governments and international bodies to enhance carbon trading. The current carbon credit prices range from 1 to 139 USD/T CO₂-e. Most importantly, more than 25 countries are trading the carbon credit of below 25 USD/T CO₂-e [73]. It is very important to enhance the carbon credit price which falls between 40 and 80 USD/T CO₂-e to satisfy CO₂ negative emissions target of the Paris agreement.

Fortunately, some countries are putting more effort into increasing carbon credit prices, such as France, where the carbon credit price went from 38 USD/T CO_{2-e} to 55 USD/T CO_{2-e} [73].

6. Apprehensions and limitations related to biochar application

Biochar has numerous applications, as detailed in the preceding sections. Biochar use is currently limited in comparison to its potential and numerous benefits. This section emphasizes some key points and scenarios that limit its widespread application.

6.1. Technical maturity

The use of pyrolysis to produce biochar has been well established up to pilot scale, and some plants are now in commercial operation [74]. Current biochar production ranges from 35000 to 70000 Ts per year, with some plans for a 5000 T/year capacity [75,76]. Recently Germany and Canada installed plants of capacity more than 50 T/annum using biomass as feedstock. Based on biomass, biochar production is at its most mature technology level up to pilot scale. A lab-scale process is still being developed for plastic, manure, and other feedstocks. Most importantly, the co-pyrolysis is also at the lab scale, which is significant for the production of biochar in the future.

6.2. Lack of market research and branding

Currently, only a small number of surveys have been conducted at the global level, with regional surveys being used to assess the potential regional market for biochar. In addition, there is a reluctance to use biochar in the market due to the lack of verified data on its usage with a smaller sample size. All available information is based on self-utilisation and research publications. As a result, a thorough market survey should be conducted to determine the precise requirement of biochar, with the option of customizing based on market demand. The reliable testing units and sample size should be available for proper branding and marketing to attract and change the perception of users.

6.3. Soil coordination

Biochar is widely regarded as the best soil enhancer, but its long residence in soil has a negative impact on soil performance and disrupts the nutrient cycle. The fixing of CO₂ emissions is the key benefit of biochar, but its long stay disturbs soil fertility and the nitrogen cycle [77]. Hence, it is very important that short-term and long-term testing field be made, and a complete data sheet is developed for fields ranging from 1 to 20 hectares for reliability [78].

6.4. Bio-coal

Pyrolysis can be used to artificially transform biomass into bio-coal, a material that resembles coal [79]. Emissions were found to reduce when bio-coal was used in place of coal in the steel and power industries. There is still a significant data sheet to be developed for the technology, however. Many researchers have begun to synthesize bio-coal and assess its market potential. For example, Lee *et al.* used the Finland scenario to investigate the market potential of bio-coal [80].

6.5. Economic value of biochar

Biochar application is limited due to a lack of economic value calculation, not for biochar production, but for its application, because biochar is commonly marketed as an environmentally friendly product. However, market demand is a less expensive solution. If substantial research is provided, the carbon credit can help to provide biochar as a cost-effective solution.

Conclusion

Due to Qatar's rapid economic growth, improved people's lifestyle, and transition towards urbanisation, it faces serious waste management problems in recent years like other developing countries. Municipal solid and animal wastes are the two main waste sources in Qatar. These two sources are high in energy/chemicals and can be converted into fuels and value-added products,

particularly biochar. As Qatar continues to expand its arable land, biochar has become one of the most sought-after commodities.

The primary goal of this research is to identify and quantify major waste sources in Qatar. Second, the study aims to estimate the amount of biochar that can be produced from the wastes, as well as the country's potential revenue from biochar. A life-cycle assessment of biochar production from all wastes is also analysed. In addition, the paper discusses market intervention and carbon trading, as well as concerns and limitations associated with biochar application.

Qatar's largest waste stream is food waste (1.8 MT), followed by wastepaper (1.3 MT). The most collected manure is poultry litter (0.82 MT), followed by sheep manure (0.46 MT), goat (0.14 MT), and camel (0.14 MT), horse (0.11 MT), and cow (0.11 MT) (0.1 MT). The production rate of biochar from wastepaper is the highest of any waste. It is expected to produce 534,969 T of biochar at 250°C and 224,286 T at 500°C. A moderate amount of biochar can be generated from poultry litter, textile waste, food waste, cow dung, and sheep manure. Wastepaper is the most lucrative waste feed source for biochar. The revenue potential is estimated at 107 million USD per year for 250°C and 45 million USD per year for 500°C. A reasonable amount of revenue can be generated from poultry litter, textile waste, food waste, cow dung, and sheep manure. Camel manure had the highest carbon footprint (0.45 kg CO₂-e at 250°C and 0.12 kg CO₂-e at 500°C).

The study recommends for a waste feedstock value chain, research development, and an integrated database to fully realise the potential of available waste sources. The next phase of research may include a more precise quantification of waste in Qatar as well as qualitative analyses, which will allow researchers, policymakers, and stakeholders to make the best decisions possible. It is hopeful that the information provided will help future research efforts and decision-making processes more effectively.

Nomenclature

CAGR	:	Compound Annual Growth Rate
CAPEX	:	Capital expenses
CDR	:	Carbon di oxide removal
EJ	:	Exa Joule
EU	:	European Union
EU ETS	:	EU Emissions Trading System
GHG	:	Greenhouse gas
GJ	:	Giga Joule
GtC	:	Gigatonnes of Carbon
LCA	:	Life cycle analysis
MCM	:	Million cubic metre
MENA	:	Middle-east and North Africa
MSP	:	Minimum Selling Price
MSW	:	Municipal solid wastes
MT	:	Million Tonne
MW	:	Mega-watt
NPV	:	Net present value
OPEX	:	Operating expenses
PSA	:	Planning and Statistics Authority
QSA	:	Qatar Statistics Authority
RGGI	:	Regional Greenhouse Gas Initiative
ROI	:	Return on Investment
TJ	:	Terra-Joule
TWH	:	Terawatt-hour
USD	:	United States Dollar

Credit authorship contribution statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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