Article

Techno-Economic Analysis of Fast Pyrolysis of Date Palm Waste for Adoption in Saudi Arabia

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Abstract: Date palm trees, being an important source of nutrition, are grown at a large scale in Saudi Arabia. The biomass waste of date palm, discarded of in a non-environmentally-friendly manner at present, can be used for biofuel generation through the fast pyrolysis technique. This technique is considered viable for thermochemical conversion of solid biomass into biofuels in terms of the initial investment, production cost, and operational cost, as well as power consumption and thermal application cost. In this study, a techno-economic analysis has been performed to assess the feasibility of converting date palm waste into bio-oil, char, and burnable gases by defining the optimum reactor design and thermal profile. Previous studies concluded that at an optimum temperature of 525 °C, the maximum bio-oil, char and gases obtained from pyrolysis of date palm waste contributed 38.8, 37.2 and 24% of the used feed stock material (on weight basis), respectively, while fluidized bed reactor exhibited high suitability for fast pyrolysis. Based on the pyrolysis product percentage, the economic analysis estimated the net saving of USD 556.8 per ton of the date palm waste processed in the pyrolysis unit. It was further estimated that Saudi Arabia could earn USD 44.77 million per annum, approximately, if 50% of the total date palm waste were processed through fast pyrolysis, with a payback time of 2.57 years. Besides that, this intervention will reduce 2029 tons of greenhouse gas emissions annually, contributing towards a lower carbon footprint.

Keywords: pyrolysis; date palm waste; techno-economic; fluidized bed reactor; biofuels

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1. Introduction

In addition to abundant oil reserves, Saudi Arabia is known for the production of delicious dates. The major crops grown in this water-scarce country include cereals, vegetables, fruits (date palm, grapes) and forage crops (alfalfa). Date palm trees are mostly grown in arid to semi-arid regions such as MENA. It has been estimated that out of total 120 million date palm trees on the planet, 23 million (19.16%) are present in Saudi Arabia. Date palm waste is generated in the form of dry leaves, stems, pits/ seeds, etc. An average date palm tree can produce 15–20 kg biomass per annum, whereas date pits account for 10% of total fruit production [1]. This indicates that 345,000 tons (23 million trees × 15 kg/tree) per annum date palm waste is produced in Saudi Arabia [2]. The date palm trees waste comprises of cellulose, hemicellulose, and lignin. Generally, this waste is burned directly on the farm or disposed of in the landfills resulting in environmental pollution. Due to highly volatile solids and low moisture contents, the date palm biomass can be transformed into biofuels (bio-oil, biochar and syn gas) using thermochemical and extraction techniques [3], thus reducing the dependence on fossil fuels.

The techniques used for the thermochemical conversion of biomass into biofuel include combustion, gasification, and pyrolysis. Date palm leaves and seeds are considered more suitable for pyrolysis compared to the leaf stem on account their of higher calorific value and volatile contents [4]. Based on the initial weight and chemical composition of the feedstock used, the pyrolysis technique produces 60–70% of liquid biofuels, 15–25% char and 10–20% gases [5]. The obtained byproducts of pyrolysis have heating value ranges of 15–30 MJ/kg (bio-oil), 17–36 MJ/kg (biochar) and 6.4–9.8 MJ/kg (syn gas), respectively [6–8].

Various research studies have indicated the potential of date palm waste pyrolysis for biofuel generation. A study recorded the production of 50%wt bio-oil, 30%wt biochar and 20%wt gas through pyrolysis of date palm biomass in a fixed bed reactor for 2 h at 500 °C. The calorific value of the obtained bio-oil was calculated to be 28.636 MJ/kg [9]. While slow pyrolysis of the date palm waste favors biochar production, the quantity of the bio-oil, biochar and gas are heavily influenced by the process temperature. A sharp decrease in the yield of biochar from 43 to 22% was observed when the thermal profile of the pyrolysis reactor jumped from 350 to 650 °C [10]. The optimum thermal profile for fast pyrolysis of date palm biomass was noted to be 525 °C where the maximum percentage of bio-oil, biochar and gas (38.8, 37.2 and 24, respectively) was achieved with energy conversion of 87% [11]. In another study, pyrolysis of date palm (feeding rate of 0.30 kg/h) in a fixed bed reactor at 500 °C with heating rate of 2000 watts produced bio-oil, char and syngas between the respective ranges of 17.0–25.9%, 31.0–36.66% and 39.0–46.33% [12]. The biochar produced after fast pyrolysis of 2 ton feedstock per batch was sold at a price of US 2.48 \$/kg [13], whereas, the price of bio-oil obtained at 330 °C was US 1.04 USD/gal [14]. The cost of pyrolytic bio-oil obtained from 100 tons of biomass per day was 0.94 USD/gal, slightly higher compared to the previous reported investigation due to variation in biomass collection and transportation rate. The cost of energy generated from bio-oil and char was calculated to be USD 6.35 MMBTU (USD 0.002 per kilowatt hour) [14].

The upgradation of bio-oil to transportation fuel is also possible after treatment. The cost of bio-oil produced from the fast pyrolysis ranges between USD 12–26/GJ. The cost of electricity and sales of char affects the cost of bio-oil production. It is estimated that around 18% of the obtained bio-oil would be used for meeting the initial electricity requirement of the pyrolysis plant [15], whereas the cost of diesel production by upgradation of bio-oil is around USD 0.56–0.82 per liter [16]. In recent years, some research articles have been published regarding techno-economics of date palm pyrolysis for biochar production to be used for soil amendments (such as neutralizing the acidity) and as a low-cost absorbent for organic and non-organic pollutant removals. However, no noticeable work has been carried out specifically targeting bio-oil production.

The objective of this study is to determine the techno-economic feasibility of thermal pyrolysis of date palm residue for production of bio-oil, biochar and syn gas while considering initial investment, cost of production and operation cost as well as power consumption and thermal applications by using the previous literature as a reference. This paper focuses on defining the potential impact of byproduct on the cost of energy production (thermal and power applications). Besides the cost estimates, the feasibility of date palm waste pyrolysis has been evaluated based on mass and energy balance. The pyrolysis processes were assessed using mass balance that controlled the quantity of the obtained products, while energy balance was employed to optimize the operational cost based on energy used or lost. The techno-economic assessment of date palm is useful for the commercialization of pyrolysis techniques as well as for calculating the production cost of biofuels and chemicals in Saudi Arabia.

2. Process Description

2.1. Date Palm Waste Analysis

For this techno-economic study, the ultimate and proximate analysis of date palm biomass waste is taken from the previous literature produced by Hussain et al., 2014 [2]. The analysis is shown below in Table 1 below.

Table 1. Ultimate and Proximate analysis of Date palm biomass.

Ultimate Analysis					
Biomass	C	H	N	S	O
Seed	44.1	6.1	0.9	0.6	48.3
Leaf	50.4	6.3	1.1	0.4	41.8
Stem	38.1	5.2	0.8	0.3	55.6

Proximate Analysis				
Biomass	Moisture	Volatile Matter	Ash contents	Fixed Carbon
Seed	5.1	75.1	9.8	8.1
Leaf	5.3	77.5	12.1	6.1
Stem	18.1	52.1	20.2	8.1

2.2. Thermochemical Conversion Process

The process of converting biomass into biofuels (gases and liquids) is either performed through biochemical, physio-chemical, or thermochemical approach. Thermochemical approach comprises super heating of biomass in the presence of some gasifying medium (air, steam, oxygen) to produce a mixture of burnable and non-burnable gases called syn gas, bio-oil, char, and tarry products. These obtained biofuels can be utilized in meeting the thermal and power needs of the local as well as industrial community, whereas the obtained char could be used for soil amendment and helps in decreasing the acidity of the soil. However, the obtained tar either went for thermal breakdown to low chain hydrocarbons or, after treatment with suitable additives, it can be used in petrochemical industry [17,18]. Figure 1 below shows three chains of processes that allow biomass to meet power demands in the form of electrical or heat energy.

Figure 1. Thermochemical routes to energy.

To carry out biochemical and extraction processes (through physiochemical technique) successfully, several tasks must be convened, such as raw materials' formulation, maintaining ideal thermal profile, and ensuring the allowable ranges of pH and other operational parameters. However, pyrolysis technique makes the system performance efficient and solves the problems of biomass handling by generating energy in a reliable and efficient manner. The biofuel and clean synthetic gas produced through pyrolysis retain 70–80% of the chemical energy.

2.3. The Principle of Fast Pyrolysis

Fast pyrolysis is a process wherein biomass undergoes breakdown into vapors under high temperature in the absence of oxidizing medium. These vapors are condensed in the form of a liquid having an energy value half of the fossil oil. Therefore, a higher yield of biofuel is required to compensate the lower energy value. A higher yield of oils up to 60% has to be ensured through fast pyrolysis at a reaction temperature of 500–550 °C at 1 atm pressure with particle residence time of 30–1500 ms (milliseconds) [8,19,20]. The factors directly controlling the bio-oil yield include feedstock type, reactor internal temperature, vapors residence time, char separation and feedstock ash contents. The maximum yield observed at 500 °C is 75% along with biochar and syn gas [21].

2.4. Pyrolysis Unit Description

The fluidized bed pyrolysis reactor used for this investigation had a capacity of 10 tons per day (dry feed stock with moisture content less than 10%). The reactor was equipped with condenser, cyclone, and gas separator. A shredder was also used for size reduction of biomass waste for a better increase heat transfer during the pyrolysis. The fluidized bed reactor act as both pyrolizer and a combustor. The dried biomass is shredded and milled before feeding into the chamber for efficient transformation into biofuels. The quality of the pyrolysis byproduct is directly affected by the biomass particle size. Therefore, the feed stock was converted into power form of <1 mm in size using the shredder [22]. The power requirement for biomass size reduction is up to 24 kWh/ton [23]. Fast pyrolytic auto thermal technique has been adopted for converting carbonaceous biomass material into oil, biochar, and condensable gases mixture. The schematic of the 10 tpd date palm auto thermal fast pyrolysis unit is shown in Figure 2 below.

Figure 2. Schematic of auto thermal pyrolysis unit.

The products of pyrolysis, such as char and gas, are separated using cyclone separator or electrostatic separator. The efficiency of the separator is around 99%. Some amount of ash remains in the oil and gas giving them a brown color. The quenching process is carried out to immediately condense the hot pyrolysis vapors (coming out of the auto thermal pyrolysis reactor) to crude bio-oil form. The pyrolytic bio-oil yield is directly affected by the condensation. Equation (1) are used to calculate the percentages of bio-oil or char and syngas, respectively [23].

$$\text{Syngas (\%)} = 100 - (\text{Bio oil})\% - (\text{Biochar})\% \quad (1)$$

3. Techno-Economic Analysis

A techno-economic analysis of biofuels production from date palm waste is required to establish its viability at commercial scale. In this analysis, the technical and economic aspects of date palm waste pyrolysis have been analyzed against each other. First, the mass and energy balances were worked out and then economic analysis was performed to estimate the cost of biofuel production and profit gain [24].

3.1. Technical Analysis

Biochemical or thermochemical techniques can be utilized for converting the date palm biomass into biofuel. The thermochemical transformation can be classified into pyrolysis, gasification, and liquefaction [25]. While pyrolysis is a promising technique to convert biomass such as lignocellulosic into fuel, it has no potential in the case of grain-based biofuels such as corn ethanol [26,27]. At present, flash or fast pyrolysis is one of the areas being most widely researched. It is considered highly promising for producing biofuels from solid biomass [28,29]. Researchers in Saudi Arabia have also described fast pyrolysis a feasible technique for deriving biofuels from date palm waste [2].

The optimum thermal profile range for carrying out biomass pyrolysis is between 450–650 °C under anaerobic conditions. The products obtained in this thermal profile include bio-oil, char, and mixture of burnable and non-burnable gases (burnable and non-burnable). Bio-oil has various advantages over unprocessed biomass given its higher volumetric energy density and economical transportation. However, lower calorific values of biofuels are noted due to the presence of oxygenated compounds and moisture contents. The presence of organic acid is another factor that makes biofuel less preferable over fossil fuels. Mostly, catalytic treatment is carried out during or after pyrolysis to minimize the ratio of oxygenated compounds in pyrolytic bio-oil.

3.1.1. Yield Assessment and Carbon Conversion Efficiency

Yield assessment and biomass conversion are important parameters required for system optimization as well as for economic analysis. The percentage of pyrolysis products can be altered by changing the operational thermal profile of the reactor. The obtained yield of the process can be estimated using Equation (2):

$$\text{Yield (\%)} = \frac{\text{Mass of product (bio oil, biochar and syngas)}}{\text{Mass of the biomass feed}} \quad (2)$$

The rate of biomass conversion into biofuels can be estimated by dividing the energy contents of pyrolysis products to the energy contents of the biomass. The mass of each pyrolysis product and higher calorific values are required for conversion estimation as shown in Equation (3):

$$\text{Conversion efficiency (\%)} = \frac{(m \times \text{HHV})_{\text{biochar}} + (m \times \text{HHV})_{\text{Bio oil}} + (m \times \text{HHV})_{\text{syngas}}}{(m \times \text{HHV})_{\text{biomass}}} \quad (3)$$

Makkawi used a bubbling fluidized bed reactor for fast pyrolysis of date palm biomass [11]. The obtained yield of the pyrolysis process comprised 37.2% biochar, 38.8% bio-oil and 24% non-condensable gas (all on dry and ash free basis). However, the bio-oil

contained 10% of moisture. One of the factors affecting the yield of bio-oil is the ash content in the biomass. The bio-oil yield has been recorded mostly between 60–70% of the initial feed weight in most of the biomass types [5]. However, theoretical calculations revealed that the efficiency of pyrolysis process using date palm waste would be up to 86.6%. Therefore, bio-oil yield in case of date palm waste was classified as low. The HHV for the bio-oil, char and non-condensable gases was calculated to be 20.88, 19.76 and 8.9 MJ/kg, respectively. The HHV of date palm biomass used in this study was taken as 18.83 MJ/kg.

3.1.2. Energy Balance of Pyrolysis Process

Table 2 presents the energy balance of processing one ton of date palm waste using fast pyrolysis unit. It abided by the law of conservation of energy which states that the input energy is equal to the output energy. The higher heating values mentioned in the above paragraph are used for these energy balance calculations.

Table 2. Energy balance for processing one ton of date palm waste from fast pyrolysis unit.

Material	Input Energy (kWh)	Pyrolysis Products from One Ton of Waste (Tons)	Output Energy (kWh)
Date palm waste, 8% MC (wet basis)	5230.5		
Bio-oil		0.388	2250.4
Char		0.372	2041.8
Syngas		0.240	593.3
Ash and heat loss from pyrolysis unit			345.0
Total			5230.5

3.1.3. Energy Requirement of Pyrolysis Process

Table 3 presents energy consumed by the pyrolysis unit for one ton of date palm wastes processed.

Table 3. Energy consumed in pyrolysis process.

S #	Steps in Pyrolysis Process	Energy Consumed (MJ/kg)	Energy Consumed (kWh/ton)
A. Electrical Energy			
(i)	Electricity consumption by fluidized bed pyrolysis unit	-	200.0 [30]
(ii)	Electricity consumed for biomass handling and pre-processing (chopping and grinding)	-	40 [30]
	Total electric energy consumed per ton		240.00
B. Thermal energy			
(i)	Drying (removal of residual moisture from 8% to zero%), about 80 kg/ton	0.3	6.66
(ii)	Heat required to raise the biomass to 500 °C and decompose it (920 kg/ton)	1.5	383.3
(iii)	Heat required to raise fluidizing gas up to 500 °C from 50 °C quenching temperature (2.75 kg of fluidizing gas per kg of biomass (Wright et al., 2010)) [31]	0.60 [30]	458.33
(iv)	Radiation, convection, and conduction losses (3% of heat input to pyrolysis reactor)	-	25.45
	Total thermal energy required per ton of date palm waste, kWh		872.74

3.2. Economic Analysis

The economic analysis of date palm fast pyrolysis was performed using the annual cost method. The annual cost is sum of the fixed cost and the variable cost of the complete pyrolysis process.

3.2.1. Fixed Cost

To estimate the per annum fixed cost of the pyrolysis unit, several assumptions were made, as shown in Table 4.

Table 4. Assumption for pyrolysis unit.

Parameters	Assumptions
Financing	100% owned capital
Pyrolysis unit availability	300 days/year
Pyrolysis unit depreciation period	8 years
Interest on investment	10%
Housing and insurance cost	2% of the initial cost of pyrolysis unit
Capacity of pyrolysis unit selected	10 tons per day
Annual capacity of pyrolysis unit for processing date palm waste	3000 tons
Total annual operating hours	7200 h

Table 5 indicates the initial cost of the complete pyrolysis unit. The capacity of pyrolysis unit was adopted to be 10 tons/day. One shredder and two storage tanks were considered for purchase. An amount of USD 0.05 million was earmarked for civil works.

Table 5. The initial cost of pyrolysis unit.

Item Description	Quantity	Price (USD Million)
Pyrolysis unit (10 tons/day capacity)	1	1.70
Shredder	1	0.05
Storage tanks	2	0.05
Civil work		0.05
Miscellaneous equipment		0.15
	Total cost	2.00

3.2.2. Variable Cost

The variable cost consists of repair and maintenance cost, labor cost, date palm wastes purchasing and transportation cost, electricity cost for pyrolysis unit and shredder, nitrogen cost for induction into reactor. Table 6 presents the assumptions made to work out the variable cost of pyrolysis unit, while Table 7 presents the fixed and variable costs per annum as well as per ton of biomass used by the pyrolysis unit.

Table 6. Assumptions to work out variable cost.

Sr #	Parameters	Assumptions
(i)	Repair and maintenance cost	2.0% of the initial cost per annum [24]
(ii)	Labor cost (3 shifts and 3 workers in each shift)	USD 30,000/worker/annum
(iii)	Date palm waste purchasing and transportation cost per ton	USD 50.00
(iv)	Electricity cost (5.4 cents/kWh in US)	0.054 USD/kWh
(v)	Nitrogen cost per ton of biomass [32]	USD 2.66
(vi)	Miscellaneous chemical cost per ton of biomass [32]	USD 4.00

Table 7. Cost analysis of biomass pyrolysis unit having capacity of 10 tons per day.

Sr #	Item	Cost USD/Annum	Cost USD/Ton of Date Palm Waste Processed	Cost USD/h of Date Palm Waste Processed
A Fixed cost estimates				
(i)	Depreciation cost	225,000	75.0	31.25
(ii)	Interest on investment	110,000	36.0	15.2
(iii)	Housing and insurance cost	40,000	13.3	5.5
	Sum of fixed cost	375,000	124.3	51.95
B Variable cost estimates				
(i)	Repair and maintenance cost	40,000	13.3	5.5
(ii)	Labor cost	270,000	90.00	37.5
(iii)	Date palm waste purchasing and transportation cost	150,000	50.00	20.83
(iv)	Electricity cost for biomass pyrolysis and pre-processing (240 kWh/ton @ 0.054 USD/kWh)	38,880	12.96	5.4
(v)	Nitrogen induction in the reactor cost	7980	2.66	1.11
(vi)	Miscellaneous chemical cost	12,000	4.00	1.67
	Sum of Variable Cost	518,860	172.92	72.01
	Total Cost (Fixed + Variable)	893,860	297.22	123.96

3.2.3. Net Revenue Generation from Pyrolysis of Date Palm Waste

Based on Makkawi's study about date palm pyrolysis, the pyrolysis products are comprised of 37.2% char, 38.8% bio-oil and 24% non-condensable gas (all on dry and ash free basis) [11]. This means one ton of date palm waste can produce 0.372-, 0.388-, and 0.240-tons char, bio-oil, and non-condensable gas, respectively, after processing through the pyrolysis unit. We may assume the selling price of biochar, bio-oil, and non-condensable gas as 1.2, 0.30 and 0.20 USD/kg, respectively. Makkawi measured the HHV for the bio-oil and char, which was 20.88 MJ/kg, and 19.76 MJ/kg, respectively. They also calculated the HHV for non-condensable gas which was 11.89 MJ/kg. As discussed earlier, the thermal energy required for pyrolysis of one ton of date palm waste was estimated at 872.74 kWh, indicating that 0.18 tons of bio-oil are required to meet the thermal energy demand of pyrolysis of one ton of date palm waste. This becomes around 38.6% of the bio-oil produced through pyrolysis of one ton of date palm waste.

Table 8 indicates that gross income from the sale of pyrolysis products obtained from one ton of date palm waste is in the tune of USD 556.8, whereas the cost of producing these pyrolysis products is in the tune of USD 297.22 (Table 7). This showed the net saving of USD 259.58 for processing one ton of date palm waste through the pyrolysis unit. It is estimated that around 345,000 tons/annum of date palm waste are available in Saudi Arabia. If 50% of this is processed through pyrolysis units, the date growers of the Kingdom can earn USD 44.77 million per annum from date palm waste, whereas the current practices of dealing with this waste are causing disposal and environmental problems for the Kingdom.

Table 8. Revenue generation from pyrolysis of one ton of date palm waste.

Item	Quantity Produced (Tons)	Quantity Consumed in the Process (Tons)	Net Quantity for Selling (Tons)	\$/Ton	Income from the Sale of Pyrolysis Products (\$)
Bio-oil	0.388	0.180	0.208	300	62.4
Biochar [33]	0.372	-	0.372	1200	446.4
Non-condensable gas	0.240	-	0.240	200	48.0
			Total revenue generated/ton		556.8
			Total revenue generated/h		232.0

3.2.4. Break-Even Analysis

The break-even point (BEP = X) in terms of cost and revenue was found as follows:

$$X = \frac{TFC}{P - V} \quad (4)$$

where:

X = Operating time in years

TFC = Total fixed cost invested in the beginning of the project

V = Total cost (fixed + variable) per annum of pyrolysis unit

P = Gross revenue generated per year through pyrolysis unit

$$X = \frac{2,000,000}{1,670,400 - 893,860}$$

$$X = 2.57 \text{ years}$$

The payback period for 10 TPD thermal pyrolysis unit was 2.57 years based on assumptions made in this analysis.

3.2.5. Net Present Value of the Pyrolysis Unit

The net present value (NPV) of the project has been calculated to determine the profitability of the project. If the NPV of a project is negative, the project is likely to fail, while a positive value indicates the chances for the project to be a success. In this project, an investment of (USD 2.0 million) was assumed to be made in the beginning of the year. Annual cash flow (annual gross revenue—annual costs) was USD 780,000. The salvage value at the end of project period (8 years) was taken as 10% of the investment (USD 200,000). The discount rate was assumed to be 10%. The NPV of this project was calculated as USD +2254, 543.6 based on the methodology presented by Smith, [34] for calculating the present equivalent of (Revenue-Costs). As the NPV is positive, the project will be beneficial provided that the assumptions made for calculating annual gross income and costs stand valid.

3.2.6. Internal Rate of Return

The internal rate of return is the rate at which an investment project promises to generate a return during its useful life. It is the discount rate at which the present value of a project's net cash inflows becomes equal to the present value of its net cash outflows. In other words, the internal rate of return is the discount rate at which a project's net present value becomes equal to zero. The prospective before-tax internal rate of return on an investment is the interest rate at which present equivalent revenues equal present equivalent costs computed on a before-tax basis. The internal rate of return for this project was calculated as 36.45% based on the methodology devised by Smith [31].

3.2.7. Other Performance Indicators

Table 9 indicates other performance parameters. It revealed that annual bio-oil production excluding bio-oil used in the pyrolysis process was 624 tons. The annual char production was 1116 tons, whereas the annual syngas production was predicted to be around 720 tons. The annual energy yield for the pyrolysis unit was predicted to be 12.12 GWh and the total energy yield calculated for the life of the pyrolysis unit was 96.96 GWh.

Table 9. Results of other performance indicators.

Sr #	Performance Indicator	Amount
1	Annual Bio-oil production	624 tons (Excluding the bio-oil consumed during the process)
2	Annual Char production	1116 tons
3	Annual syngas production	720 tons
4	Annual energy yield	12.12 GWh
5	Total energy yield during the life of the pyrolysis unit	96.96 GWh
6	Levelized cost of energy	0.048 \$/kWh
7	Simple payback time	2.57 years
8	Annual GHG emission reduction	2029 tons of CO ₂

The projected levelized cost of energy generation was 0.048 \$/kWh. This was calculated by discounting net cash flows of the project to the equivalent net present value costs at the first year when the plant commenced operation and dividing the results with total energy yield during the life of the project. The simple payback period for the pyrolysis unit was 2.57 years. The annual capacity of pyrolysis unit for processing date palm waste was estimated 3000 tons, which is expected to produce biochar capacity of 1116 tons per year. The value of carbon content of biochar 0.62 and carbon stability 0.80 has been adopted from literature for medium temperature pyrolysis [32–34].

$$\text{GHG credit from biochar} = \text{biochar (tons)} \times \text{carbon content of biochar (\%)} \times \text{carbon stability (\%)} \times \frac{44}{12} \quad (5)$$

The annual reduction in GHG (Greenhouse Gases) emissions was anticipated to be 2029 tons of carbon dioxide by using Equation (5). All performance indicators affirm that the project is feasible, technically as well as economically.

4. Conclusions and Recommendations

- (i) Fast pyrolysis is regarded as a promising technology to derive bio-oil, biochar, and non-condensable gas from biomass.
- (ii) This techno-economic analysis affirmed the feasibility of fast pyrolysis of date palm waste, based on the experimental data. However, it is necessary to operate pilot plant for a reasonably long period to collect more reliable first-hand data for determining optimal operational conditions and for making this analysis more reliable.
- (iii) The economic analysis revealed that a date grower can secure net saving of USD 556.8 by converting one ton of date palm waste into biofuel through fast pyrolysis.
- (iv) If 50% of date palm waste produced in Saudi Arabia is converted into biofuel through fast pyrolysis, a net amount of USD 44.77 million per annum can be earned.
- (v) The payback period of a fast pyrolysis unit having 10 tons/day capacity was worked out to be 2.57 years. The net present value of this project was positive, and internal rate of return was calculated as 36.45%.
- (vi) It was observed that the most sensitive parameter for the economic analysis was the selling price of the byproducts (bio-oil, biochar, syn gas) of fast pyrolysis unit, particularly, the price variation of biochar is very high. In this analysis, the average selling price of biochar was considered.
- (vii) Based on the findings of this techno-economic analysis, it is recommended to frame a research and commercialization project of biomass energy generation in Saudi Arabia. This will help in exploring the potential of biomass energy resources and suggest adoption of appropriate technologies in the Kingdom based on scientific research.

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Abbreviations or Acronyms

Atm	Atmosphere
MENA	Middle East and North Africa
HHV	Higher Heating Value
$m \times \text{HHV}$	Higher Heating Value of the products based on mass
MJ	Mega Joules
wt %	Weight percent
Gj	Gega Joules
Ms	Milliseconds
kWh	Kilo Watt hour
GWh	Giga Watt hour
TEA	Techno-economic Analysis
CV	Calorific Values
Tpd	Tons per day
BEP	Break Even Point
TFC	Total Fixed Cost
X	Operating time in years
V	Total cost (fixed +variable) per annum
P	Gross revenue generated per year
NPV	Net Present Value
IRR	Internal Rate of Return
GHG	Green House Gas

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