A comparative techno-economic analysis of combined oil and power production from pyrolysis and co-pyrolysis plants utilizing rice straw and scrap rubber tires

Shoaib Raza Khan[a*], Muhammad Zeeshan[a], Salsabeel Fatima[a], Daniel Ciolkosz[b], Ioanna Dimitriou[c], Hongyue Jin[d]

[a]Institute of Environmental Sciences of and Engineering (IESE), National University of Sciences and Technology (NUST), Islamabad, Pakistan.

[b]Department of Agricultural and Biological Engineering (ABE), Pennsylvania State University, University Park, PA, 16802, USA

[c]Department of Chemical and Environmental Engineering, Faculty of Engineering, University of Nottingham, Nottingham, NG7 2RD, UK

[d]Department of Systems & Industrial Engineering, University of Arizona, 1127 East James E. Rogers Way, Tucson 85721, AZ, USA

[*]Corresponding Author (Email: shoaibraza104@yahoo.com)

Abstract

In this study, three pyrolysis and co-pyrolysis plants processing rice straw (RS)[1]and scrap rubber tire (SRT) to produce oil and power (i.e., electricity) at 30 t/hr capacity are simulated using SuperPro Designer software. The objective of the study is to comparatively evaluate the techno-economic performance of hypothetical (co-)pyrolysis plants at commercial scale. The RS

Nomanclature: RS, rice straw; SRT, scrap rubber tire; NPV, net present value; PBT, payback period; IRR, internal rate of return; GM, gross margin; TEA, techno-economic assessment; RoI, return on investment; VLE, vapor-liquid equilibrium; EPC, equipment purchase cost; HHV, higher heating value; DC, Direct cost; PPMJ, price per mega Joule; DFC, direct fixed capital; IC, Indirect cost; TPDC, total plant direct cost; CFC, contractor's fee & contingency

production is estimated in 36 districts of Punjab, Pakistan through GIS mapping and the location and capacity of the plants are selected accordingly. The RS plant has the lowest capital and annual operating costs of $53.70 million and $43.70 million, respectively however, it is not economically feasible under current conditions due to its low quantity and quality of the produced oil. The base cases of SRT and co-feed (RS and SRT) plants are found to be viable with capital costs of $66.90 million and $68.30 million, and annual operating costs of $77.20 million and $70.30 million respectively. The co-pyrolysis plant produces the highest oil (main product) yield of 74 kilotons annually and power of 4801 KWe with the lowest unit production cost of $950/tonne. Consequently, the co-pyrolysis plant offers the highest economic performance with $35.55 million of net present value (NPV) estimated at a discount rate of 15% over 20 years of plant life. The payback period (PBT), internal rate of return (IRR) and gross margin (GM) are 5.08 years, 34.67% and 21.35% respectively. Sensitivity analysis suggests that the NPV is sensitive to the oil selling price, feedstock cost, and capital investment for all plants. Moreover, economy of scale analysis quantified the effects of different processing capacities on the economic metrics such as NPV, PBT, capital cost, and operating cost.

Keywords: Biomass; Scrap rubber tire; Co-pyrolysis; Techno-economic assessment; Process modelling; SuperPro Designer

1 Background

The implementation of circular economy in the agriculture sector requires incentivization of biofuel production from biomass wastes as a way of achieving renewable energy and solid waste management targets simultaneously [1,2]. Biofuels have been deemed critical in the development of future transportation despite the development of electric vehicles [3–5]. In 2018, biofuels provided 93% of all renewable energy utilized in transport, whilst the rest was contributed by renewable electricity (e.g. wind and solar) [6]. Co-pyrolysis of biomass and petroleum-based feedstocks such as scrap rubber tires (SRT) or waste plastic is a promising approach that could serve as a “bridging technology” as the world economy is shifting towards renewables [7,8]. A total of 769 million tons (Mt) of rice straw (RS) was produced worldwide in 2018, which indicates its copious availability for bio-fuel production. Moreover, the global production of SRT is also increasing due to various factors. The management of these two wastes is an important topic worldwide. Techno-economic assessment (TEA) of co-pyrolysis of RS and SRT plants will yield valuable insights into potential of co-pyrolysis as an important component of emerging bioeconomy and circular economy.

Various aspects of (co-)pyrolysis have been extensively studied inter alia operating parameters [9–11], reaction kinetics [12–16], types and pre-treatments of feedstock [17–19][20], catalytic [21–25] non-catalytic co-pyrolysis [26–28]. However, only a few studies have investigated the techno-economic viability of sole biomass or plastic waste (co-)pyrolysis. For instance, gasoline and petrol production from aspen wood was modelled by Patel et al. (2019) with a plant capacity of 2000 Mg d^{-1}. The production costs of \$1.04 and \$1.09 per litre were observed for gasoline and diesel, respectively. Unrean et al. (2018) studied the comparative techno-economic and environmental performance of three techniques including pyrolysis in batch mode at capacity of 1 tonne (t) rice straw. The estimated production cost of 1 MJ of energy was found to be \$0.043 with the limitation that only energy balance was considered while the capital, other operating and maintenance costs were overlooked. Likewise, TEA of hemicellulose, cellulose and lignin pyrolysis was investigated by Shahbaz et al. (2020) reporting that lignin produced 2.5 and 2.4 times more biochar than holocellulose and therefore lignin pyrolysis was more viable. However, established profitability metrics such as gross margin (GM), return on investment (RoI), payback period (PBT), internal rate of return (IRR) and net present value (NPV) are overlooked in majority of the published studies. Similarly, very few studies have covered sensitivity analysis. In addition, previous literature mainly investigated the modelling of pyrolysis of sole biomass where the selling price of the oil is not computed based on its quality. Generally, the pyrolytic products and particularly, the oil yield is of low quality, when biomass alone is used as feedstock. Hence, few studies investigated the bio-oil upgrading through hydrodeoxygenation at extremely high pressure [29,32]; however, commercialization of such intricate system could be challenging particularly during the early stages of commercialization of pyrolysis.

The pyrolysis technology is already demonstrated at different commercial scales by different organizations worldwide. The plant constructed by the Empyro group in Hengelo, the Netherlands has biomass processing capacity of 5 t/h and produces oil, steam and electricity [33]. Likewise, another pyrolysis plant is constructed in Lieksa Finland which produces 24,000 t of bio-oil from sawmill residue annually [33]. On the flipside, New Hope Energy, which is already operating small scale plant in Tyler, has proposed to build a new plastic pyrolysis plant along the Gulf Coast of Texas with a capacity of 100,000 t/year [34]. Similarly, waste tire-based commercial plants of pyrolysis are also operating worldwide. The experimental and muddling studies and pilot and commercial scale plants, operated worldwide, reflect that pyrolysis technology is feasible and scalable. However, most of the plants are processing the petroleum-based feedstock or catalytic pyrolysis of biomass feedstock, which is hydrogen deficient, are commercialised to the best of authors knowledge. Conversely, co-pyrolysis has been reported to be an effective alternative strategy for production of superior quality oil and other by-products and management of agricultural and plastic/tire waste simultaneously. Despite the tremendous potential, the transition of co-pyrolysis from a laboratory/bench scale technology to an economical commercial-scale business venture has yet to be achieved due to numerous technical, economic, and project developmental obstacles. The paucity of understanding of the techno-economic performance of the co-pyrolysis at the commercials scale is one prime factors. TEA is an effective modelling tool for examining these challenges and assessing the interplay of system performance, project configuration, and financial scenario on the overall performance of a biofuels production facility. The results of TEA can be used to guide research and technology development, as well as provide guidance to policy and investment decisions with respect to renewable biofuels [35]. However, the limited availability of various input data including processing performance and assessing the costs of equipment and accessories is a significant challenge.

Hitherto techno-economic viability of co-production of oil and power through co-pyrolysis of RS and SRT has not been investigated. In one of our previous studies, we found that co-pyrolysis is a more viable technique compared to pyrolysis of biomass or waste tires [36]. However, such plants produced a substantial amount of non-condensable gases that can be utilized to produce electricity besides meeting the on-site energy requirements. In addition, the selection of a suitable plant site is also a key factor that influences transportation cost of the biomass and thus the overall profitability. Moreover, previous studies mainly investigated techno-economics considering only liquid biofuel as sole product. The present study investigates the oil and power production from co-pyrolysis of RS and SRT from higher capacity plants compared to previous studies. First, the RS production has been estimated in all districts of Punjab, which is the most important province of Pakistan from an agricultural perspective, to select the prime location for the pyrolysis plants. Second, the influence of different scenarios such as variable selling prices of oil (based on its quality compared to various commercial fuels) on the economics of co-pyrolysis plants has been investigated. The capital investment, production cost and revenues are estimated. In addition, the economic analysis also provides insights into various economic parameters such as NPV, PBT, RoI, and GM. Furthermore, variations in profitability of the plants due to changes in input variables such as raw material procurement cost, product selling price, utility cost, labor, discount rate, operational hours and interest rate has also been studied through comprehensive sensitivity analysis. Third, the impacts of economies of scale have been investigated to understand the economic performance of the plants at various scales. It is anticipated that output of the study will provide valuable inputs to policymakers, waste management organizations and investors worldwide and facilitate the commercialization of co-pyrolysis as a waste-to-energy approach. Ultimately, the commercialization of pyrolysis technology could improve energy security and diversify the energy portfolio, particularly for developing and net energy importing countries, such as Pakistan.

2 Methods

2.1 Plant site selection and crop residue estimation

Punjab is the main province of Pakistan which produces a variety of agricultural residues, such as RS, wheat straw, sugarcane bagasse and cotton stalks [37,38]. The district-wise availability of RS in Punjab has been estimated, for the 2020-2021 period using the following equation [39].

$$C_m = P_m \times GSR \times D \times \frac{\omega_m}{100} \times \eta_c \quad (1)$$

where C_m is the amount of residue (t/year) available for collection in district *m*. P_m represents the annual production of rice crop (t/year) in district *m* which is obtained from the Agriculture Department Punjab, (2020). The GSR corresponds to grain to straw ratio, and D denotes the dry matter content for the RS, which are taken as 1.5 [41] and 0.85 [42] respectively.

The percentage of RS residue left on the field for collection in district m is designated by ω_m. Moreover, the residue collection efficiency is assumed to be 70% which is represented by η_c.

ω_m is a critical parameter for the estimation of C_m. RS is harvested by both, manual and mechanical modes in Pakistan, which influence the value of ω_m. It has been reported that mechanical harvesting produces more ω_m compared to manual harvesting [30]. Therefore, the proportion of the manual and mechanical harvesting practices are considered for the calculation of ω_m using equation 2 below:

$$\omega_m = A_m \times \alpha_m + B_m(1 - \alpha_m) \tag{2}$$

In equation 2, A_m and B_m correspond to the proportion of residue left on the field for collection after mechanical and manual harvesting, respectively, for district m. The proportion of RS harvested mechanically in district m is designated by α_m, hence $1 - \alpha_m$ indicates the proportion of RS harvested manually. The A_m, B_m and α_m parameters have been assessed through a field survey reported earlier for multiple districts of Pakistan [43]. The calculations have been performed using MS Excel® (Microsoft office 365) and thereafter data set is incorporated into the shapefile for administrative district boundaries of Punjab using ArcGIS 10.8 for RS mapping.

2.2 Model and process description

The three pyrolysis scenarios examined here have been modelled using systems modeling software (SuperPro Designer V.13, Intelligen corporation, Scotch Plains, NJ, USA). The model includes all steps from farm-gate procurement of 30 t/hr of feedstock through to sale of products from factory-gate. Three types of plants are simulated. Two pyrolysis plants process only RS and SRT while the third is a co-pyrolysis plant of RS and SRT (20:80). Fig. 1 shows the process flow diagram of the co-pyrolysis facility.

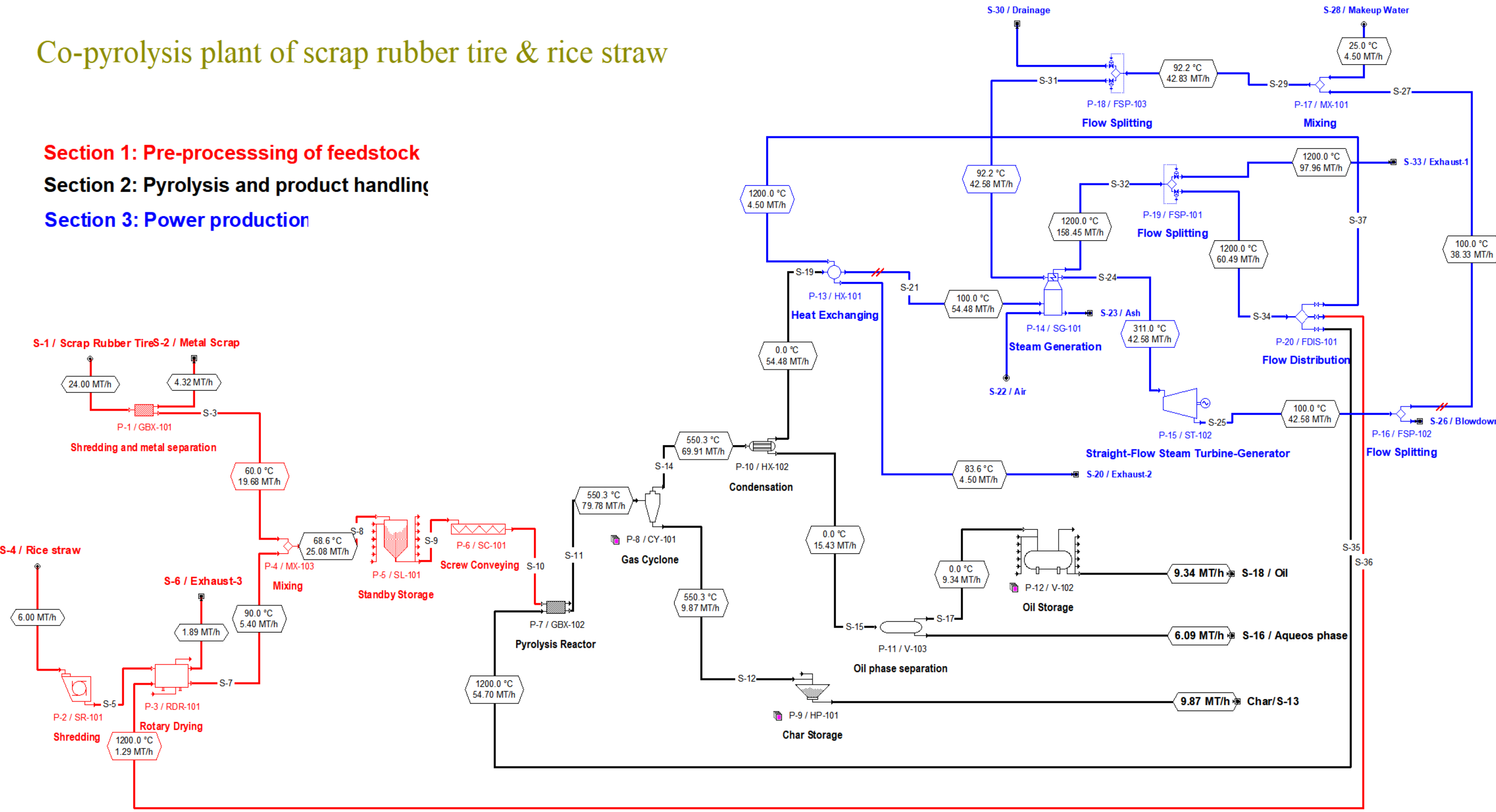

Figure 1: Process flow diagram of co-pyrolysis plant of scrap rubber tire and rice straw

Each process model is divided into three subsystems: a) feedstock pre-processing shown by red icons and streams, b) pyrolysis and product handling (including oil) represented by black icons and streams and c) power production through steam turbine represented by blue icons.

2.2.1 Feedstock pre-processing

The feedstock pre-processing segment is unique from the other two segments in terms of unit operations and conditions due to the different nature of two feedstocks. Therefore, pre-processing (e.g., shredding) of SRT and RS is carried out separately in the co-pyrolysis plant. The two pre-processed feedstocks are then passed into a mixer prior to be fed to the pyrolysis reactor, as shown in Fig. 1. Initially, the SRT is fed into the shredder (P-1) to produce the tire crumb. Steel wire is used in tire manufacturing to improve its shock absorbing capacity and strength and contributes around 15-20% of the SRT mass at the end of their life [44]. The SRT shredder is designed to separate 18% of the mass as steel wires or metal scrap which are represented by stream S-2. The SRT moisture content has been assumed to be zero due to the high hydrophobic nature of the tire rubber and, therefore, no drying unit is proposed for SRT. The RS shredding is performed in the shredding unit P-2 while a rotary dryer (P-3) is used for its drying. The exhaust gases of the boiler are recycled back, through stream S-36, into the rotary drier with a flow rate of 1.29 t/hr. The stream S-3 of shredded SRT and stream S-7 of the RS are mixed in the mixer P-4 to ensure a homogenous blend of feedstock for better synergistic effects [45,46]. Additional standby storage for mixed co-feed (P-5) is also considered for 3 hours to ensure smooth operation of the pyrolysis plant in case of malfunctioning of the feedstock pre-pre-processing units.

2.2.2 Pyrolysis and product handling

The pyrolysis reactor is the major component of the pyrolysis plant which is modelled using a generic box (P-7). The conversion of feedstock into pyrolysis products is carried out through continuous stoichiometric reactions which take place at a temperature of 550 °C and pressure of 1 atm. Moreover, the enthalpy of the co-pyrolysis reactions was calculated by the model to be 823 kJ/kg which is comparable to the relevant literature [47]. The reactants, RS and SRT, are converted into three products namely oil gas and char. The composition of oil and gas fractions can be found in our previous study [8]. Flue gases of the boiler (P-14) are recycled back, through stream S-35, into the reactor to maintain the temperature of reactor. The char is separated from the volatiles using a cyclone (P-8) and stored in a char storage hopper (P-9). The volatile stream S-14 is sent to the condenser where oil and non-condensable vapor streams are separated at a temperature of 0 °C using $CaCl_2$ brine as a cooling agent. The separation of each component and vapor-liquid equilibrium (VLE) calculations are performed using Raoult's law with Antoine coefficients of the components. The oil stream S-15 is comprised of both organic phase and aqueous phase compounds which is fed into the phase separation unit (P-11). The two phases are separated based on the partition coefficients of each component of the input stream. Horizontal storage tank (P-12) is used for storage of oil while the aqueous phase is assumed to be an aqueous waste that needs suitable disposal. The char and oil storages are sized for 10 days to allow for minor potential fluctuations in the market.

2.2.3 Power generation

The vapor stream S-19 from the condenser is comprised of hydrogen, methane, oxides of carbons and other gases. The absolute condensation of vapours, other than non-condensable gases, cannot be achieved in the condenser due to vapor-liquid equilibrium (VLE). Therefore, fractions of other hydrocarbons including toluene, benzene, ethyl benzene, xylenes and oxygenates were also present in the stream. This stream is preheated to 100 °C in a heat exchanger P-13 through recycled stream S-36 from the boiler. The preheated stream is combusted in a boiler P-14 to generate steam at a pressure of 100 bar and saturation temperature of 311 °C. An excess oxygen level of 5% is used in the boiler to ensure the complete combustion of fuel, while the boiler flue gas temperature is set at 1200 °C. The low percentage of excess air is important to keep the oxygen level low in the recycled stream S-37 to avoid combustion in the pyrolysis reactor. Power is produced from the steam through a straight-flow steam turbine-generator (P-15) with 85% efficiency [48]. The steam expansion calculations are based on the analytical isentropic expansion model, while condensate recovered from the turbine is at 100 °C. Condensate blowdown of 10% is considered from the boiler in every cycle as shown by P-16. The makeup water of 4.5 t/hr is added to the returning condensate through a mixing unit P-17 and fed into the boiler maintaining a recycled water loop.

2.4 Estimation of process costs and revenues

2.4.1 Capital investment and operating cost

The capital investment is mainly broken down into direct fixed capital (DFC), start-up cost and working capital. The DFC represents the total capital needed for the design, construction and installation of a plant and is categorized into the direct cost (tangible assets), indirect cost, contingency and contractor fee. The equipment purchase cost (EPC) is the major component of direct cost which was determined first using the SuperPro Designer cost database for the majority of the equipment used. Then EPC of tire shredder, pyrolysis plant and oil storage tanks were updated through various quotes from vendors and adjusted to the required capacities using power law [36]. Where necessary, equipment costs were updated to the 2022 values using current inflation rate. All other direct cost components were calculated as fractions of EPC using lang factors [49], as shown in Table S1. The construction overhead and engineering costs were calculated as 35% and 25% of the direct capital cost as given in Table 1 [50]. The potential uncertainty and error in cost estimation were taken into account in the form of a contingency cost equal to 10% of the sum of direct and indirect costs. In addition to fixed capital investment, working capital and start-up cost are two other important cost components of capital investment. Working capital for raw material, utilities, labor and waste treatment costs is calculated by multiplying 30 (the number of days in the start-up period) by the corresponding unit costs per day.

Operating costs of the pyrolysis plants include the cost of raw materials, utilities, taxes, labor, maintenance and waste treatment or disposal, as shown in Table S1. The cost of feedstock is \$210/t and \$80/t for SRT and RS, respectively. The SRT cost was provided by the pyrolysis plant operators and tire suppliers in Pakistan and does not include the storage cost as tire rubber is not degradable. The RS procurement cost was taken from the proposal of the National Electric Power Regulatory Authority (NEPRA) Pakistan for the determination of a new upfront tariff for electricity generation from biomass power projects in Punjab, Pakistan [51]. A maintenance cost of 10% (EPC) was assumed which is higher than the typical maintenance cost (6%) as these plants are handling solid, liquid and gaseous materials at high temperatures and have moving parts [52]. The labor cost was estimated considering local basic salary rates and other factors [49] such as benefits (0.2), operating supplies (0.10), supervision (0.2), and administration (0.6) using equation 3. The details of the labor allocation have been provided in the supplementary information (SI).

$$\text{Labor cost} = \text{Basic rate} \times (1+ \text{benefits} + \text{operating supplies} + \text{supervision} + \text{administration}) \times \text{labor hours} \quad (3)$$

Other components of the operating cost are shown in Table S1. Considering the type of the pyrolysis plants under study, all lang factors considered for the estimation of the direct and indirect costs correspond to a solid-fluid process [49]. Other economic evaluation parameters such as plant capacity and life, discount rate, interest rate, corporate tax, inflation, operating hours and loan details are provided in Table 1.

Table 1: Other parameters for economic evaluation

Economic parameters	Value	Source
Year of analysis	2022	
Plant size	30 t/h	
Plant life	20 years	[53]
Annual operating hours	7920	[54]
Discount rate*	15%	[55]
Inflation*	25%	[56]
Debt:equity (only for DC)	75:25	[51]
Construction period	24 months	[51]
Interest rate (KIBOR)[a*]	15.29%	[57]
Corporate tax**	29%	[58]
Salvage value	0	[50]
Depreciation period	10 years	[54]
Depreciation method	Straight line	[59]
Power law scaling factor	0.7	[60]
Exchange rate (USD/PKR)	239.252	[61]

[a]Karachi Inter Bank Offer Rates

2.4.2 Products selling prices

Oil, electricity, char and steel wire are the revenue streams. Oil is the main product from the plants and its selling price is critical for the profitability. The oil selling price is calculated based on the selling price and heating value of commercial fuels, such as diesel and petrol, using the following equations.

$$\text{Selling Price of Oil}_X = \text{HHV}_X \times \text{PPMJ}_Y \quad (4)$$

$$\text{PPMJ}_Y = \left(\frac{\text{Selling price of Y}}{\text{HHV of Y}}\right) \quad (5)$$

where X corresponds to the pyrolysis oil sample from SRT, RS or co-feed and HHV is the higher heating value of the respective oil sample. PPMJ represents the price per megajoule of the reference fuel Y (diesel or petrol). For the base cases, the selling price of oil is calculated using diesel as a reference fuel. The heating value and selling price of the commercial fuels and pyrolysis oils are provided in Table S2. Moreover, the market for char is immature compared to that of oil and therefore, only a single market price was used for all char samples which is provided by a pyrolysis plant operating company in Pakistan. The electricity selling price is adopted from NEPRA Pakistan, while the market price of steel wire is used for profitability analysis.

2.4.3 Profitability analysis parameters

The economic performance of the plants has been analysed through various economic parameters such as GM, ROI, PBT, IRR and NPV which are calculated using following equations.

$$\mathrm{GM} = \left(\frac{\text{Gross profit}}{\text{Revenues}}\right) \times 100 \tag{6}$$

$$\mathrm{RoI} = \left(\frac{\text{Net Profit}}{\text{Total investment}}\right) \times 100 \tag{7}$$

$$\text{Net profit} = (\text{Gross profit - tax} + \text{depreciation}) \tag{8}$$

$$\text{PBT (years)} = \left(\frac{\text{Total investment}}{\text{Net profit}}\right) \tag{9}$$

$$\mathrm{NPV} = \sum_{y=1}^{n} \left(\frac{\mathrm{NCFy}}{(1+i)^{y}}\right) \tag{10}$$

In equation 10, “n” indicates the plant life while “NCF” is the net cash flow in year “y”. Likewise, “i” denotes the discount rate at which the future cash flows are discounted.

2.5 Sensitivity analysis

The economic performance of the commercial scale plants will be influenced if operational and economics parameters as well as product selling prices fluctuate during the service life of. The magnitude of the impacts triggered by variations in feedstock cost, utility cost, labor cost, discount rate, inflation rate, interest rate and product selling price are appraised through sensitivity analyses. The base values of the parameters are varied by ± 30% following the parameters fluctuation trends in similar studies [59] except the plant operating hours which are changed by ± 10 since they cannot exceed the number of hours in a calendar year (8760). In addition, sensitive analyses are also performed for the plant construction phase to analyse the impacts of capital investment variations on NPV. The study estimates are carried out considering the cost of only major equipment and therefore, accuracy can vary around ± 30%. In addition, the other components of direct costs, indirect costs, contingency, contractor fee and start-up costs are estimated using various lang factors which can be ± 20% accurate [60]. This suggests that variations can be expected in the range of ± 50% under market fluctuations, inflation and other factors.

3 Results and discussion

3.1 Plant location

The district-wise RS production of study area is shown in Fig. S1. It is conspicuous from the map that the Gujranwala district has the highest RS production per square kilometre (139 t/sq.km) with total production of 0.42 Mt followed by Sheikhupura (0.36 Mt). The annual RS requirements for RS pyrolysis and co-feed pyrolysis facilities are 0.24 Mt and 0.05 Mt, respectively, which is further discussed in section 3.2. The prime location for the pyrolysis plants is Gujranwala due to the highest RS production and it is adjacent to the other RS producing districts as shown on map (Figure S1). This region also has a mature road and transportation network which could ensure efficient transportation of feedstock and final products. The cumulative amount of available RS for energy production from the aforementioned region is 1.13 Mt which is approximately 5 times greater than the proposed capacity of an RS pyrolysis plant (0.24 Mt). This indicates that a larger amount of RS can be procured economically to the facility from the adjacent districts if the plant capacity is increased in the future.

3.2 Mass and energy balance

A total of 30 t/hr feedstock is processed in all three conceptual plants. In the co-pyrolysis plant, the available co-feed flow rate is 25.08 t/hr after drying of RS and elimination of steel wire from SRT. The tire shredder separates 4.32 t/hr (18%) of steel wires and 19.68 t/hr SRT rubber was mixed with 5.4 t/ hr available RS. The oil and char yields obtained from the co-pyrolysis plant are 9.34 t/ hr and 9.87 t/hr, respectively. Similarly, 24.60 t/ hr and 27 t/ hr of feedstocks are available in pyrolysis plants of SRT and RS respectively. The oil and char yields in SRT plant are estimated to be 8.99 t/ hr and 10.33 t/ hr while 4.62 t/ hr and 9.45 t/ hr are estimated in case of RS plant respectively. The highest oil yield was achieved in co-pyrolysis plant while highest char yield was obtained from SRT plant. Consistent source of thermal energy is required for the endothermic reactions of pyrolysis. This heat is provided to the pyrolysis reactor through recycling of boiler flue gases. The enthalpy of 823 kJ/kg of co-pyrolysis reaction is calculated by the process model. Accordingly, the flue gases stream S-35 with mass flow rate of 54.70 t/hr is recycled back to maintain the temperature of the reactor. The enthalpies of reactions for RS (450 kJ/kg) and WT (1168 kJ/kg) pyrolysis plants are different and therefore, recycled streams have different mass flowrates of 56 t/hr and 68.5 t/hr in respective models. Besides, the annual electricity requirements of RS, SRT and co-pyrolysis plants to run the equipment such as shredders, mixers, flow adjusters and pumps etc. are 2968.5 kW_e, 2973.5 kW_e and 3174 kW_e respectively. The highest electricity consumption for co-pyrolysis plant is due to separate pre-processing units for the two feedstocks and an additional co-feed mixer. The power production from RS, SRT and co-pyrolysis plants is 787 kW_e, 4277 kW_e and 4801 kW_e. The SRT and co-pyrolysis plants produce more electricity than the plants requirements which contributes to revenue generation. Unlike SRT and co-pyrolysis plants, electricity production of the RS plant was insufficient to power the plant, meeting only 27% of electricity requirements.

3.3 Economic analysis

3.3.1 Capital cost

The total cost of capital for all three modelled plants scenarios is shown in Table S3. The major component of the capital cost is EPC which is the highest for the co-pyrolysis plant ($9.34 million) followed by the SRT ($9.02 million) and RS plants ($7.69 million). This is due to additional equipment needed for pre-processing of two feedstocks including shredders, a rotary drier and a mixer. Moreover, the oil production is also the highest for the co-pyrolysis plant which necessitates more storage capacity, thereby contributing to the increased capital cost. Additionally, the combustion of the non-condensable gases from the co-pyrolysis plant produced more steam compared to the other plants due to the oxygenates in the co-pyrolysis product gas. Therefore, a larger capacity steam turbine with higher cost was required which increased the overall EPC of the plant. The capacities and purchase costs of major equipment for all three plants are provided in Table S4. The equipment cost of the SRT pyrolysis reactor is the highest due to higher enthalpy of the SRT pyrolysis reactions which necessitated a higher mass flow rate of the recycled gas stream to provide the required energy. This, ultimately, increased the size and cost of the reactor compared to the other two plants. As elucidated in section 2.4, the other components of the direct cost are estimated as fractions of EPC which is the highest for the co-pyrolysis plant therefore, its total direct cost is also the highest among all three pyrolysis cases at approximately $60 million. Similarly, the co-pyrolysis plant had the highest indirect cost, contractor's fee and contingency cost. The total capital investment for the co-pyrolysis plant is $ 68.317 million which is circa 27% and 2% higher than the capital investment required for the RS plant and SRT plant, respectively.

3.3.2 Operating costs

The comparative operational costs required to run the pyrolysis facilities are given in Table 2. The RS plant has the lowest operating cost at $43.745 million while the highest operating cost of $77.185 million is estimated for the SRT plant.

Table 2: Operating costs ($) of the pyrolysis facilities and share (%) of individual component

Cost item	**RS plant**		**SRT plant**		**Co-feed plant**	
	Cost	Share	Cost	Share	Cost	Share
Raw materials	19,084,000	43.62	50,063,000	64.86	44,059,000	62.64
Labor-dependent	74,000	0.17	88,000	0.11	102,000	0.14
Maintenance	9,290,000	21.24	11,164,000	14.46	11,543,000	16.41
Laboratory/QC/QA	11,000	0.03	13,000	0.02	15,000	0.02
Waste disposal	389,000	0.89	278,000	0.36	241,000	0.34
Utilities	14,897,000	34.05	15,579,000	20.18	14,377,000	20.44
Total	43,745,000	100.00	77,185,000	100.00	70,338,000	100.00

The cost of raw materials is the main contributor to the operating costs followed by utilities, maintenance, waste disposal, and labor for all plants. RS is cheaper than SRT and therefore contributes less to the operating cost of the RS and co-pyrolysis plants. Utility costs, which include the cost of electricity and coolant in the condenser, are the highest for the SRT plant at circa $15.60 million followed by the RS and co-pyrolysis plant at $14.90 million and $14.40 million respectively. The amount of coolant required to decrease the temperature of vapours in condenser is increased in the SRT plant due to the larger flow rate of the recycled stream to the pyrolysis reactor; therefore, coolant costs are higher in this case. Overall utility costs are slightly higher for the RS plant compared to the co-pyrolysis plant. This is due to the purchase electricity and higher RS feedstock available from the pre-processing section and consequent higher volatile generation compared to co-feed. The third major component of operating costs is maintenance which is the highest for the co-pyrolysis plant at $11.5 million due to additional pre-processing equipment needed for both feedstocks compared to the other two plants where only one type of feedstock is processed. The waste disposal cost is attributed to the management of aqueous phase separated from the oil. The RS pyrolysis produced the highest amount of aqueous waste thus resulting in higher disposal costs.

3.3.3 Revenue generation and unit production cost

The economic summary of capital investment, operating costs, annual production, unit production cost, revenues and profitability indicators are provided in Table 3. For all plants, oil is the main revenue stream with the co-pyrolysis plant having the highest annual production of 74 kilo tonnes followed by the SRT (71 kilo tonnes) and RS facility (37 kilo tonnes). The selling price of oil produced from the co-pyrolysis facility is slightly lower than that of SRT however, the higher co-pyrolysis yield contributed to the highest main revenue generation at $77.4 million. On the other hand, the quantity and quality of RS oil is the lowest among all which generates the lowest revenue of circa $68.00 million. After pyrolysis oil, electricity co-produced in the pyrolysis facilities contributed the highest to the revenue of co-pyrolysis plant (6.40% of total revenue) followed by revenues from char and steel wires. Similarly, electricity is the main revenue contributor, after oil, for the SRT plant followed by steel wire and char. The unit production cost and unit production revenues are calculated with reference to the main product stream (oil) indicated by the term “MP” in Table 3. The unit production cost, calculated by dividing the annual operating cost by the total oil production, is the highest for the RS plant ($1.20/kg) and the lowest ($0.95/kg) for the co-pyrolysis plant due to the difference in the oil yield of these two cases. Moreover, the SRT plant has a higher unit production cost ($/1.08/kg) than the co-pyrolysis plant due to the higher procurement cost of SRT than that of RS. Similarly, the unit production revenue is highest for the SRT plant at $1.23/kg despite bearing higher unit production costs compared to the co-pyrolysis plant.

Table 3: Economic summary of the (co)-pyrolysis plants

Parameters	**Plant type**					
	RS*	SRT*	Co-feed*	RS**	SRT**	Co-feed**
Capital investment (M $)	53.73	66.91	68.32	55.93	66.912	68.32
Operating cost (M $)	43.75	77.19	70.34	67.98	77.19	70.34
Main revenue (oil) (M $/year)	13.91	74.67	77.41	14.94	76.74	79.55
Electricity (M $/year)	0.94	5.08	5.70	0.94	5.08	5.70
Total revenues (M $/year)	18.60	87.22	89.43	21.11	89.28	91.57
Production (Kilo tonne MP/year)	37.00	71.00	74.00	37.00	71.00	74.00
Unit production cost ($/kg MP)	1.19	1.08	0.95	1.19	1.08	0.95
Unit revenue ($/kg MP)	0.55	1.23	1.21	0.58	1.25	1.24
Gross margin (%)	- 117.7	11.50	21.35	- 107.1	13.55	23.19
Return on investment (%)	- 44.03	10.65	19.84	- 42.12	12.84	22.07
Payback time (years)	N/A*	9.39	5.04	N/A*	7.79	4.53
IRR (After Taxes) (%)	N/A*	15.56	34.67	N/A*	19.90	38.09
NPV (M $)	-153.85	1.10	35.56	-148.77	9.14	42.17

* Base cases where oil selling price is calculated using diesel as reference fuel
** The cases where oil selling price is calculated using gasoline as reference fuel
N/A* represents the extremely low values which could not be estimated

3.3.4 Profitability

The profitability indicators of the conceptual pyrolysis plants including GM, RoI, PBT, IRR) and NPV, indicate that the co-pyrolysis plant is the most economically viable option (Table 3). Conversely, all the economic indicators for the RS plant were unfavourable due to the lower quantity and quality of oil produced suggesting that this option is not feasible. When diesel is used as reference fuel for the product selling price, the GM is 9.85% higher for the co-pyrolysis plant (21.35%) than the SRT plant (11.50%). The co-pyrolysis plant with a shorter PBT of 5.08 years compared to that of the SRT plant (9.39 years), is the most suitable alternative for the investors. The PBT of the co-pyrolysis plant lies within the typical PBT range of 2 to 7 years for biomass processing plants [54] while the longer PBT for the SRT plant is due to the higher unit production costs. Similarly, the IRR of the co-pyrolysis plant is 34.67% while that of the SRT plant is 15.56%. It has been reported that bioenergy projects with IRR in the range of at least 10-15% are acceptable [54,62]. Moreover, the IRR of the co-pyrolysis plant is more than double the minimum IRR (15%)

proposed by the NEPRA, Pakistan for electricity generation from the biomass plant in the Punjab district [63]. The NPV of the co-pyrolysis plant is $35.56 million (diesel as reference fuel), while that of SRT and RS plant is $1.10 million and $-153.85 million. respectively. The difference in NPV of the plants is attributed to the difference in their annual cash flows.

The revenues and economic indices were improved for all plants configurations when selling price of the oil were calculated with reference to the selling price of commercial gasoline. However, the economic indices of RS plant remained negative, as shown in Table 3. The PBT was reduced from circa 5 years to 4.50 years for the co-pyrolysis plant and from 9.40 years to 7.80 years for the SRT plant, The IRR and NPV of all plants increased reaching circa 38% and $42 million, respectively for the most feasible option of co-pyrolysis. Although profitability of all plants was improved in case of gasoline as reference fuel compared to base case where diesel was used as reference fuel to calculate the selling prices of the oil, further analysis such as sensitivity and economies of scale were performed using base case.

3.3 Sensitivity analysis

The results of the sensitivity analysis for the RS, SRT and co-feed plants are illustrated in tornado plots shown in Fig. 2 (a, b and c respectively). The NPV is found to be more sensitive to the oil selling price and SRT cost for the SRT and co-pyrolysis plants, while the RS price is the most sensitive parameters in case of the RS plant. For the RS plant, the positive NPV is not achievable within the analysed range of inputs (+30) which signifies that this option is unlikely to be economically viable without substantial economic support. The NPV of co-pyrolysis and SRT in the optimistic scenario is increased to $100.684 million and $83.129 million respectively. compared to the base values of $17.857 million and $1.101 million Although market factors can influence the oil selling price in either direction, the lower selling price will significantly compromise the economics of the plants. Therefore, the stability of oil selling prices must be ensured through robust policies, tariffs and subsidies to attract investors and policy makers. The SRT procurement cost is the next most influential parameter which will necessitate at least its stability or reduction to ensure the economic operations of the plants. For the RS plant, the NPV is most sensitive to the RS price which also significantly influences the NPV of the co-pyrolysis plant. The undesirable RS price increases could be prevented by establishing long-term contracts with various biomass supplying companies to supply the biomass under fixed quantity and procurement cost. The discount rate, interest rate and other parameters also influence the NPV; however, the magnitude is lower for the SRT and co-pyrolysis plant.

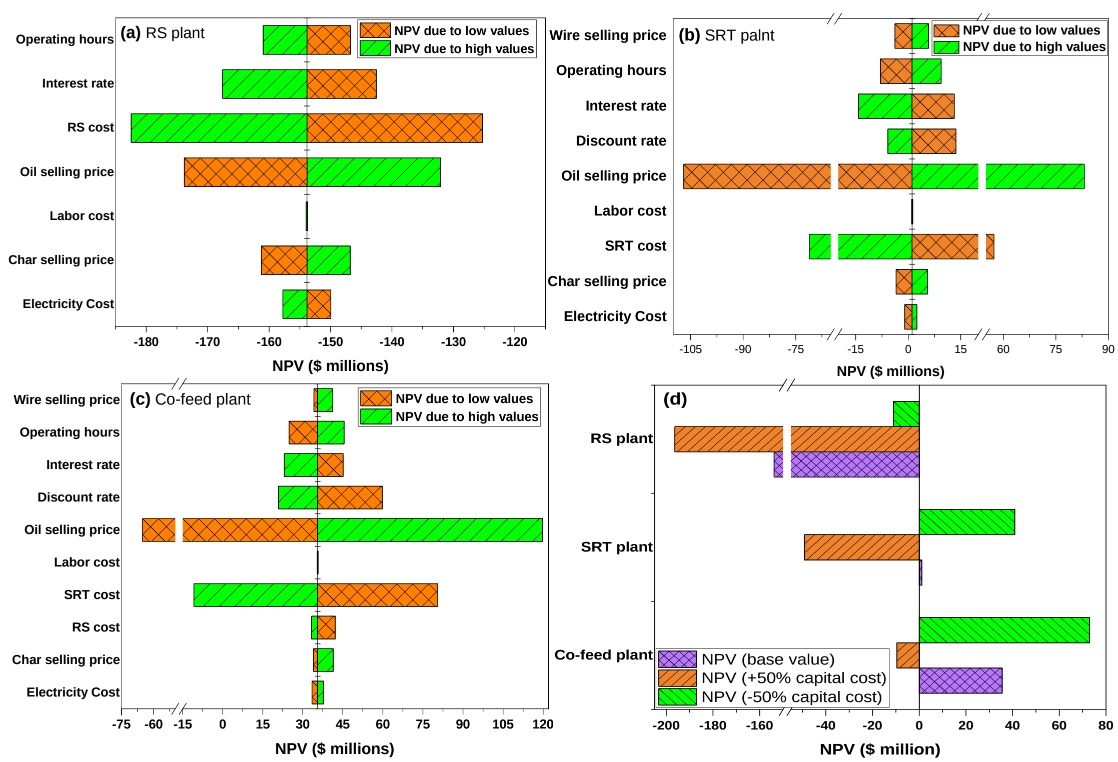

Figure 2: Sensitivity analysis for NPV of (co-) pyrolysis plants

The NPV is found to be most sensitive to capital costs for the SRT pyrolysis plant however, the highest NPV of $ 72.94 million is observed for the co-pyrolysis plant when capital cost reduced by 50% compared to base cost.

3.4 Economies of scale

Fig. 3 shows the impact of varied plant capacities on the capital costs, operating costs, unit production costs, PBT and NPV compared to the base capacity (30 t/h) for the co-pyrolysis plant. The capital and operating costs, IRR and NPV were decreased while the unit production costs and PBT were increased for a smaller capacity plant (15 t/h).

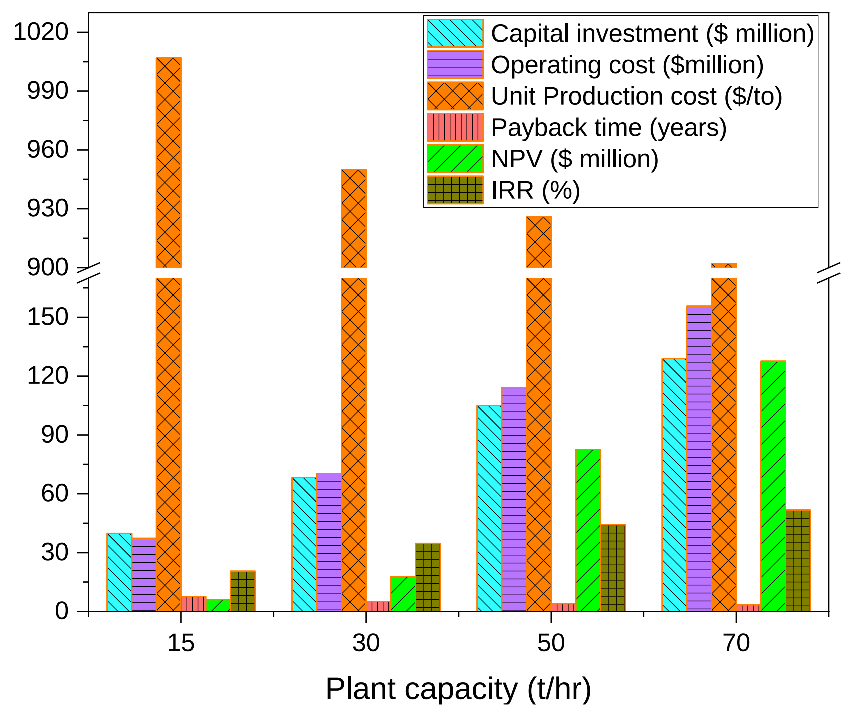

Figure 3: The economies of scale analysis for co-pyrolysis plant

All economic indices remained favourable with the PBT being circa 7.64 years which is still lower than the PBT of the base SRT plant. This reflects that a smaller co-pyrolysis facility is also lucrative and can be installed at decentralized locations to support the local rural economy. For the larger capacities (50 and 70 t/hr), the capital and operating costs, IRR and NPV increased while the PBT and unit production cost decreased compared to the base case due to spreading out expenditures over higher production units. The highest capacity plant (70 t/hr) has a capital investment, operating cost, unit production cost, PBT, IRR and NPV of $128.87 million, $155.66 million, 902 $/tonne, 4.40 years, 51.76% and $127.65 million, respectively. The unit production cost of the 70 t/hr case is 5.15% lower, whilst the NPV is 259% higher than that of the base case. This is attributed to the higher annual revenue from the larger annual production.

4 Conclusions

Techno-economic assessment of the (co)-pyrolysis plant of rice straw (RS) and scrap rubber tire (SRT) was performed through simulation using experimental data. Even though the RS plant has the lowest capital and operating cost, its unit production cost of $1.19/kg is highest due to poor oil yield and quality rendering it infeasible with negative economic indices. This is due to the lower oil yield and its poor quality compared to diesel or gasoline. Sensitivity analysis indicates that economic performance of the RS plant remains negative even under optimistic scenarios of selling price and operating costs. Conversely, the base cases of both SRT and co-pyrolysis plants are both profitable; however, the economic performance of the co-pyrolysis plant is more favourable with higher NPV, PBT, IRR and GM of $35.56 million, 5.08 years, 34.67% and 21.35% respectively. The profitability of both SRT and co-pyrolysis plants improved when the selling price of oil is calculated using gasoline as reference fuel, nonetheless the co-pyrolysis plant performance is still superior under this scenario. The PBT was reduced from circa 5 years to 4.5 years for the co-pyrolysis plant and from 9.30 years to 7.79 years for the SRT plant The IRR and NPV of all plants also increased in this case to a maximum 38% and $42 million, respectively, for the co-pyrolysis plant. The sensitivity analysis indicates that the selling price of the oil, feedstock (SRT and RS) costs and capital investment significantly influence the NPV and other economic indices. This reflects that robust policy and subsidies are required to limit the price volatility of raw material and products for stable economical operation of the facilities. SRT are procured from the China and import cost is used for analysis. Alternatively, Pakistan produces significant amount of SRT which can be collected and used in co-pyrolysis thereby decreasing its procurement cost. Moreover, undesirable RS price increases could be prevented by establishing long-term contracts with various biomass supplying companies to supply the biomass under fixed quantity and procurement cost. Moreover, a policy can be devised to promote and subsidize RS utilization by engaging the farmers where profit can be shared with them ultimately diversifying the rural economy.

Acknowledgments

The authors would like to acknowledge Demetri Petrides and Intelligen, Inc., Scotch Plains, NJ 07076, USA for providing access to the SuperPro designer software to execute this research. The author also would extend gratitude to Dr. Nikiforos Misailidis for his technical support for the model development. Besides, the National University of Sciences Technology (NUST) Islamabad and the Higher Education Commission (HEC) of Pakistan are also regarded for their support.

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