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Energy and techno-economic analysis of aviation fuel production via biomass gasification, olefins synthesis and oligomerization

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ABSTRACT

Bio-based aviation fuel is crucial for reducing carbon emissions in aviation. To address the limitations of poor selectivity inherent in traditional Fischer-Tropsch (F-T) synthesis technologies, this study introduces a novel approach: producing olefins via F-T synthesis after gasification, then generating aviation fuel through olefin oligomerization. A simulation model was developed to evaluate the energy efficiency of different feedstocks through process optimization and parameter analysis. The economic viability was assessed via discounted cash flow method and sensitivity analysis. Results indicate that the gasification process significantly influences the overall energy efficiency and yield, as the operational parameters affect the quality and ratio of CO and H_2 in the produced syngas. The optimal gasification conditions are 850 °C and a steam-to-biomass ratio of 0.5, yielding energy efficiencies for the corn stover-to-aviation fuel (CS-AF) and poplar-to-aviation fuel (P-AF) scenarios are 44.5 % and 39.96 %, respectively. Different biomass types exhibit variations in composition, leading to differences in the yield and energy efficiency of the final product. The minimum fuel selling prices (MFSP) for CS-AF and P-AF are $1713.58/t and $1307.77/t, respectively, with the lower cost of poplar feedstock in the P-AF route being a key factor contributing to its superior economic viability. Further research reveals that MFSP is most sensitive to aviation fuel yield, highlighting the importance of optimizing technology to improve yield. Additionally, the gasification plant should exceed 1200 t/d capacity to mitigate scale effects. This study provides an innovative technical model for bio-aviation fuel production and serves as a valuable reference for its commercial application.

1. Background

As economic globalization progresses and human technology advances, air transport has become increasingly vital for economic trade and international exchanges, positioning aviation fuel as one of the key transportation fuels, just behind gasoline and diesel for vehicles [1]. According to data from the International Civil Aviation Organization (ICAO), the international aviation industry consumed about 142 million metric tons of fuel in 2010, and it is projected that fuel consumption will continue to grow by 2.8–3.9 times by 2040 [2,3]. Concurrently, the International Air Transport Association (IATA) stated in 2016 that the global number of air passengers is expected to double within 20 years, increasing from 3.8 billion to 8.2 billion by 2037 [4].

The continuous growth of the aviation industry poses a series of environmental impacts. Traditional jet fuel, primarily derived from petroleum, has the disadvantages of high carbon dioxide emissions and being non-renewable [5–7]. In 2022, carbon dioxide emissions from aviation fuel accounted for approximately 2 % of the total global anthropogenic emissions [8,9]. In addition to this, the emissions of nitrogen oxides (NO_x), water vapor, and particulate matter from the aviation industry may lead to the formation of contrails or vapor trails from aircraft, which further exacerbates global warming [10,11]. Therefore, to address the sharp increase in global demand for aviation fuel and to vigorously promote the aviation industry's emission reduction tasks, the extensive development and use of bio-aviation fuel with low pollutant emissions and environmental friendliness have been incorporated into the sustainable development strategic goals of the aviation industry by many countries and regions [12–15].

The production process of bio-aviation fuel mainly includes biomass gasification and Fischer-Tropsch (F-T) synthesis technology [16–18],

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esters and fatty acids hydrogenation technology [19,20], as well as biomass fermentation and upgrading technology [21–23]. Among them, biomass gasification and F-T synthesis technology primarily convert biomass into a mixture of gases such as H_2 and CO (syngas) through gasification pathways, which is then converted into liquid hydrocarbon compounds through the F-T reaction under the action of a catalyst [24]. By altering the H_2/CO ratio of the syngas, the type of catalyst, and the temperature and pressure of the F-T reaction, the carbon number of the product can be directionally controlled, thereby enabling the preparation of bio-aviation fuel [25–27]. Gasification and F-T synthesis technology can not only utilize a variety of biomass feedstocks but also have strong emission reduction capabilities and moderate economic viability, which will become an important process method for the production of bio-aviation fuel in various countries around the world in the future. Currently, the F-T synthesis process has passed the ASTM-D7566 standard certification, and the fuel it produces can be directly mixed and used in aircraft or conventional jet aircraft, with a mixing ratio as high as 50 % [26,28]. However, the traditional method of directly producing aviation fuel from syngas through F-T synthesis faces the disadvantages of poor selectivity and low yield [29]. To address this issue, our study utilizes iron-based catalysts to steer the F-T reaction towards the production of low-carbon olefins, which are subsequently oligomerized into aviation fuel with the aid of acidic catalysts. This path can achieve high selectivity of olefins towards the conversion of aviation fuel, effectively solving the problem of poor selectivity in the direct F-T synthesis of aviation fuel.

According to IATA research, economic viability and technological maturity remain the main obstacles to the commercial production of bio-jet fuel [30]. Product yield and system energy efficiency are important criteria for evaluating technological maturity. Li et al. [31] conducted process simulation and calculations for the production of jet fuel from corn stover gasification and F-T synthesis, finding that the yield of jet fuel was 8.64 %. The exergy efficiency of bio-jet fuel and the exergy efficiency of the system were 22.78 % and 49.8 %, respectively, with major energy losses attributed to internal energy consumption. Shi et al. [32] explored the utilization pathways of residual lignin in the hydrothermal conversion process of corn stover for jet fuel production, discovering that the system energy conversion efficiencies for lignin hydrothermal upgrading, gasification fermentation, and combustion were 32.75 %, 32.67 %, and 31.44 %, respectively. In addition to the innovation of aviation fuel production technology, assessing the economic viability of the aviation fuel production process is also very important for its subsequent large-scale promotion. Many scholars have conducted route design and economic research on the F-T production process of bio-jet fuel, hoping to find ways to improve the economic viability. Research shows that the type of biomass feedstock has a significant impact on the economic viability of F-T synthetic fuel [33]. Atsonios et al. [21] used wood chips as feedstock for the F-T reaction to prepare aviation fuel, and found through Aspen Plus simulation analysis that the minimum fuel price was €1.24/L, and the price of biomass feedstock has a significant impact on this value. Jong et al. [34] found through simulation research on the biomass gasification F-T synthesis process that when using forestry residues as gasification feedstock, the minimum fuel price of jet fuel was €1.65/t, which was €0.65/t lower than the minimum fuel price when using wheat straw as the feedstock. Li et al. [35] utilized straw as the feedstock for biomass gasification and F-T synthesis. They simulated the process flow for two scenarios where steam was used for heating and power generation. The calculated production costs for jet fuel in these scenarios were $699.41/t and $863.02/t, respectively, both of which were higher than the cost of petroleum-based jet fuel at $568.79/t.

Based on the aforementioned, both domestic and international research has already conducted route studies and systematic evaluations for biomass gasification and F-T synthesis technology. However, the biomass gasification-olefins-oligomerization (GOO) route, which has higher selectivity for aviation fuel, is still primarily in the laboratory research and industrial pilot stages. There is a lack of comprehensive assessment of the system's energy efficiency, and the commercialization level of this route is low. Additionally, there is a scarcity of economic data, which makes the economic situation unclear.

To fill the gap in this area of research and to address the environmental impacts caused by the continuous growth of the aviation industry, it is crucial to develop high-selectivity and high-conversion biomass aviation fuel production technologies. The aviation industry significantly contributes to global CO_2 emissions and other pollutants, which exacerbate global warming. Therefore, to meet the urgent need for emission reduction in the aviation industry, the extensive development and use of bio-aviation fuel with low pollutant emissions and environmental friendliness have been incorporated into the sustainable development strategic goals of many countries and regions.

In this context, this study aims to achieve the following objectives: (1) to integrate biomass gasification technology, syngas F-T olefin production technology, and olefin oligomerization technology using Aspen Plus to develop a biomass GOO process with high selectivity. Additionally, incorporate real-world data from the entire process flow to enhance the reliability of the model and the results; (2) to conduct energy analysis and techno-economic analysis to provide technical references and policy-making suggestions for the demonstration and commercial application of this process; and (3) to evaluate the impact of different feedstock types on the economic viability of the technology by selecting poplar and corn stover, two typical forestry and agricultural waste materials, as research objects. This study represents the first systematic simulation study of producing aviation fuel via the biomass GOO route, which has not been reported elsewhere. The structure of this paper is as follows: Section 2 presents the process of model establishment for the GOO sub-systems. Section 3 introduces the selection of optimal operating conditions for the designed GOO system and the corresponding energy efficiency. It also analyzes the capital investment and cost accounting of the system, and further assesses the economic viability of the plant and the profitability of the product. The conclusion is drawn in the final section.

2. Research method

2.1. Process route of the biomass GOO system for producing aviation fuel

The main steps of the biomass GOO process for producing aviation fuel are as follows: Biomass is gasified to convert into syngas (Stream 3), then CO and H_2 in the syngas are converted into C_2-C_4 olefins (Stream 13) under the action of related catalysts, and the olefins further undergo oligomerization reactions to ultimately produce aviation fuel. Based on the aforementioned process route, the operating procedure shown in Fig. 1 was designed, which includes steps such as syngas purification, olefin separation, and product separation.

In addition, the heat from the gas cooling process and the olefin production process in the entire system is recovered by generating steam. The off-gas (Stream 19 and Stream 21) from the olefin production process and the oligomerization process is combusted, and the heat generated is first used to provide heat for the gasification and tar reforming processes, with the surplus used for steam production. After meeting the system's consumption, the generated steam drives the turbine to perform work and produce electricity.

2.2. Process simulation of the biomass GOO system for producing aviation fuel

Based on the aforementioned process flow, the biomass GOO system was constructed using Aspen Plus V11, which includes five parts: biomass gasification, syngas purification and conditioning, conversion of syngas to olefins, olefin oligomerization, and combustion & steam-water system, as shown in Fig. A1.

During the simulation process, the property method is set to PR-BM,

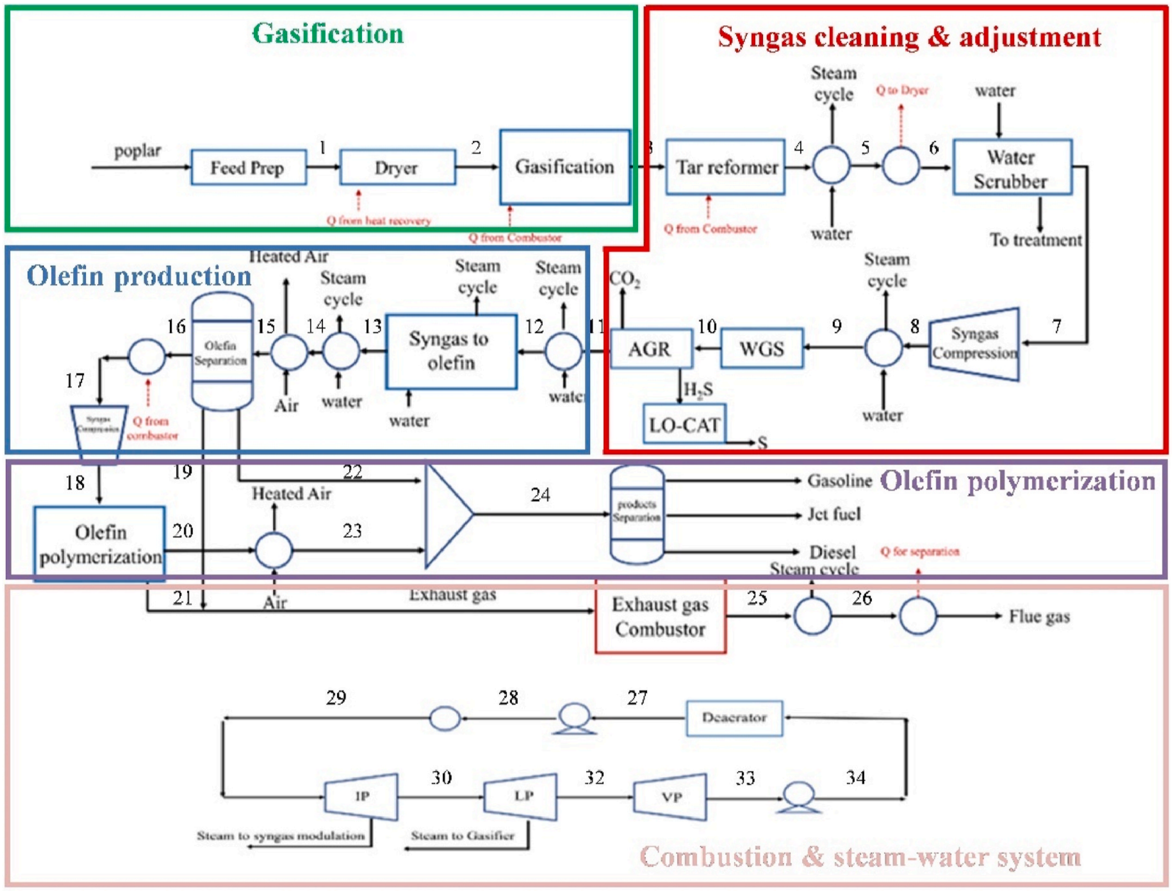


Fig. 1. Schematic flowchart of biomass GOO production system for aviation fuel.

and the stream type is set to MIXCINC, indicating that the system uses both mixed and nonconventional (NC) solid streams. NC solids refer to materials that cannot be represented by molecular structures, including poplar wood, corn straw, and ash used in this study. The physical properties of the nonconventional components are calculated through elemental analysis and proximate analysis. Ash content is considered inert. The enthalpy model is HCOALGEN, and the density model is DCOALIGT. The elemental and proximate analyses for the two types of feedstocks are presented in Table A1. These data are based on our team's experimental measurements and characterizations.

2.2.1. Biomass gasification

Since the subsequent conversion processes mainly utilize H_2 and CO in the syngas, to increase the proportion of H_2 in the syngas, this study selects steam as the gasification agent with a steam temperature of 150 °C. Additionally, to facilitate olefin synthesis, we regulated the mass flow rate of steam introduced during gasification to ensure the steam-to-biomass ratio (S/B) post-gasification was maintained as close as feasible to 2. This operational target was prioritized to align with the optimal range for efficient olefin formation in subsequent catalytic stages. In Aspen Plus, the gasification process of biomass is mainly characterized by the RYield and RGibbs methods [36]. The role of RYield is to convert the nonconventional biomass components into conventional components, while RGibbs mainly predicts the distribution and composition of the products based on the minimum Gibbs free energy of the reaction [37]. Due to the short residence time in the gasifier, it is difficult for the actual gasification process to reach chemical equilibrium. Therefore, in this study, we use a restricted equilibrium approach in the RGibbs block to simulate the gasification process. Specifically, we select the option 'Restrict chemical equilibrium - specify temperature approach or reactions' in the RGibbs block. We then define individual reactions with a zero temperature approach specification. This means that the RGibbs block calculates the chemical equilibrium constant for each reaction at the reactor temperature, providing the equilibrium gas composition. Biomass gasification is a complex process involving several chemical reactions, and the reactions considered in this work are listed in Equations (1)–(8) in Table A2 [38]. The simulation of the gasification process also considers the production of tar, and the composition of tar is assumed to be C_6H_6 [36].

Based on the aforementioned settings, this study verifies the accuracy of the gasification model using the gasification conditions from reference [38], where the gasification temperature is 700 °C, the ratio of steam to biomass is 0.5, and the feedstock is forestry waste, with its elemental and proximate analysis shown in Table A3. The data for the forestry waste were sourced from reference [39]. The comparison of the model simulation results with the literature is shown in Table 1.

It can be observed that the simulated values of H_2, CO, and CO_2 have good agreement with the literature results, while the simulated value of CH_4 has a certain deviation from the literature value. The reason for this deviation is that the generation of large molecular hydrocarbons was neglected in the construction of the gasification model [36,38]. It is important to note that similar deviations in CH_4 values have been reported in other studies, with CH_4 deviations ranging from 80.5 % to

Table 1
Results of gasification model validation.

Gas composition	Simulation	Literature
H_2	54.2	57.9
CO	32.6	35.6
CO_2	9.6	9.2
CH_4	3.6	1.6

93.5 % [40–42]. These studies have mentioned that such deviations are a common issue in equilibrium modeling. Considering that equilibrium models neglect significant gasification issues such as system kinetics and fluid dynamics, this relative error is deemed acceptable. Moreover, CH_4 is present in a relatively small amount in the entire gasification product, while H_2 and CO are the main feedstocks for subsequent synthesis, so the model can effectively describe the gasification process.

2.2.2. Syngas purification and conditioning

The raw syngas produced by gasification must be purified before it can be further converted and utilized. At the same time, the subsequent olefin production process requires the H_2/CO ratio in the syngas to be around 2 [43]. Therefore, before olefin production, it is also necessary to adjust the composition of the syngas. In this paper, the gas purification and adjustment module mainly includes four steps: tar reforming, water washing, water-gas shift (WGS) reaction, and acid gas removal. The Aspen Plus process simulation diagram is shown in Fig. 2.

The raw syngas (S1) first passes through a cyclone separator (SEP) to remove ash and other solid impurities, and then enters the tar reforming unit (REFORMER). The primary function of the tar reforming unit is to convert hydrocarbons such as tar and methane into CO and H_2 under the influence of steam [36]. The tar reforming reactor is characterized using the Rstoic module, and the conversion rates of the related reactions are set according to the literature [44]. The reforming temperature is 890 °C, and the amount of steam used is 2 mol H_2O/mol C [44].

After reforming, the syngas (S4) is cooled down and enters the water washing unit (SCRUBBER). This step serves two purposes: it further cools the syngas and also removes residual impurities, particulates, and unconverted tar from the syngas. The water washing unit is simulated using a Flash model, with the water flow rate set to 1/4 the mass of the syngas. The temperature of the Flash is controlled by design specifications to achieve a H_2O/CO molar ratio of 1 after washing [45].

The purified syngas (S10), after compression, enters the WGS unit (WGS) for the adjustment of the syngas composition. Since this study uses steam as the gasification agent, the raw syngas already has a relatively high H_2/CO ratio. Therefore, only the high-temperature WGS process is selected, with process parameters of 340 °C and 2.6 MPa. The REquil module is used to simulate this process, with design specifications controlling the steam flow rate into the WGS reactor to maintain the H_2/CO ratio at 2.

The adjusted gas (S13) contains a large amount of H_2S and CO_2. The presence of these gases can lead to catalyst poisoning and deactivation in the downstream synthesis of olefins, so it is necessary to remove acidic gases before entering the olefin synthesis unit. The Rectisol process, developed by the German companies Linde and Lurgi, has a very high solubility for acidic gases and can effectively remove H_2S and CO_2. Therefore, this study selects the Rectisol process for the removal of acidic gases, and the removal rates for CO_2 and H_2S in the entire acidic gas removal unit (B12) are set at 95 % and 99 % respectively [46,47].

2.2.3. Conversion of syngas to olefins

Syngas undergoes the F-T reaction in the olefin preparation unit to produce light olefins. The carbon number of the F-T reaction products is limited by the Anderson-Schulz-Flory (ASF) distribution, making the design of high-performance catalysts crucial for the direct production of olefins from syngas through the F-T reaction. Based on this, our team has developed the FeMnK/Meso C catalyst, which efficiently promotes the F-T reaction towards the production of light olefins. Under the action of this catalyst, the syngas primarily generates olefins (ethylene, propylene, butylene, and a small amount of C_{5+} olefins), alkanes (methane, ethane, propane, butane, and C_{5+} alkanes), CO_2, and water. The specific reaction equation that occurs is as follows:

$$(n+1)H_2 + nCO \rightarrow C_nH_{2n+2} + nH_2O \quad (1)$$

$$2nH_2 + nCO \rightarrow C_nH_{2n} + nH_2O \quad (2)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (3)$$

In this text, the Rstoic reactor is used to simulate the process of converting syngas into olefins. Based on our team's experimentally research findings, the reaction performance reaches a distinct maximum under optimized operational parameters of 320 °C and 2.0 MPa. The input reaction equations are as shown in equations (1)–(3), and the conversion rate is calculated based on CO. The distribution of components after the reaction is shown in Table A4. These data are derived from our previous experimental studies, which are incorporated to

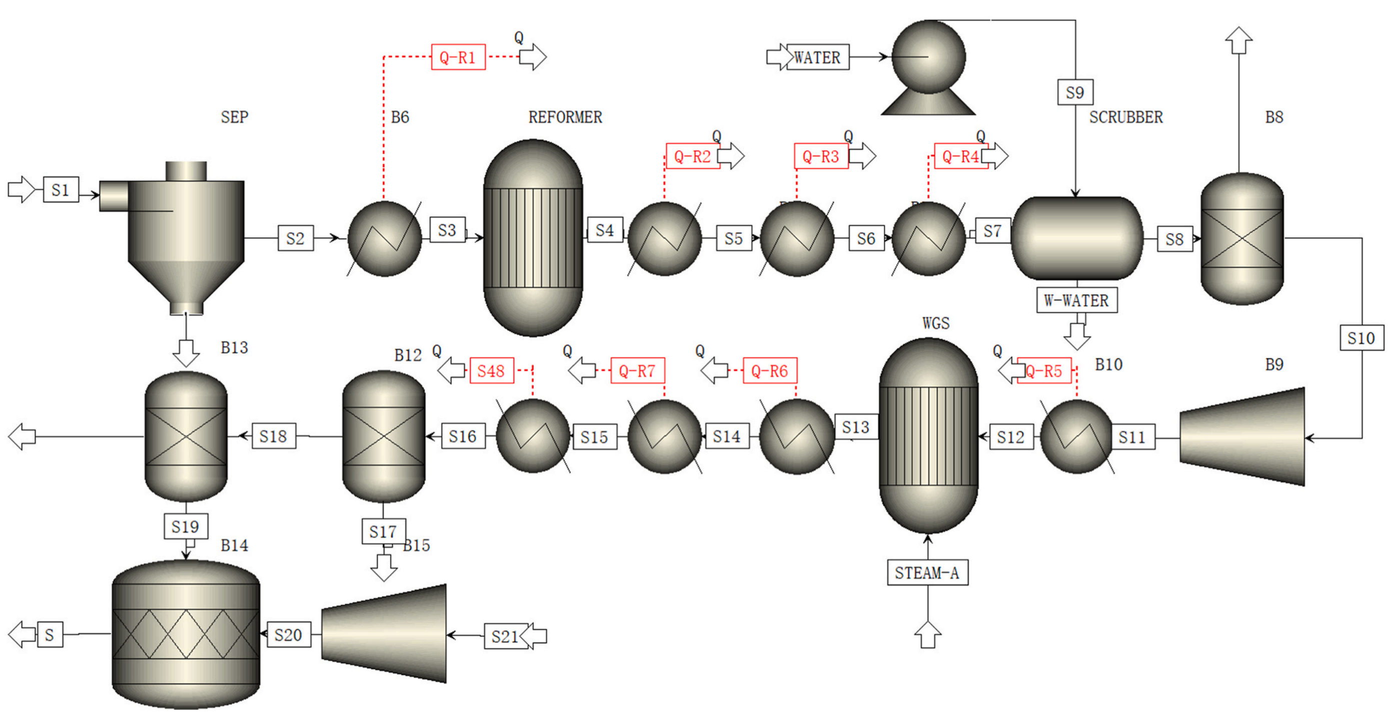


Fig. 2. Aspen Plus process simulation diagram for the gas purification and adjustment module.

enhance the reliability of the model and the results.

To enhance the efficiency of olefin oligomerization and mitigate the inhibitory effects of alkanes in the product stream on conversion rates, targeted separation of components within the reaction products is essential. This step ensures preferential retention of reactive olefins while removing alkane byproducts that could compromise reaction kinetics in downstream oligomerization stages. The process of olefin separation mainly follows the methodology outlined in Ref. [48]: firstly, separate the C_{5+} components from the products, then remove CO_2, and finally, complete the separation of olefins and alkanes in separation towers. The simulation of each separation tower in this part mainly uses the Sep module. The separated olefins enter the olefin polymerization unit.

2.2.4. Olefin oligomerization

Based on our team's previous experimental research findings, we utilized a nickel-based catalyst supported on ZSM-5 to convert light olefins into fuels with varying carbon numbers during the simulation. The oligomerization process of olefins is simulated using the RYield module, with reaction parameters set at 270 °C and 4 MPa, based on the optimal conditions determined from the experiments. The conversion rate of olefins in this process is 90 %, and the specific product distribution is shown in Table 2. The liquid products generated from this process are separated together with the C_{5+} components produced in the olefin production stage to obtain gasoline, aviation fuel, and components above C_{16}, while the remaining off-gas is sent to the combustion system for heating the entire system.

2.2.5. Combustion & steam-water system

This study recovers the heat generated by the cooling process of internal gases in the entire system by producing steam. The synthesis gas to olefin and olefin oligomerization processes are strongly exothermic reactions, and the temperature of the reactor must be controlled within a certain range during the reaction. Therefore, the cooling process of the reactor generates a large amount of steam [49], which is used to heat the olefin separation and product separation processes. The combustion process mainly involves burning organic waste from the entire production process to produce the steam required by the system. The simulation of the combustion reactor uses the RGibbs module, with a temperature set at 870 °C [50], and to ensure complete combustion of the off-gas, the air volume entering the combustion furnace is determined by design specifications, controlling the excess air coefficient during the combustion process to 1.2. The flue gas composition is generated by the simulation based on the set reaction temperature. The heat generated by combustion is used to produce steam, which first meets the system's energy consumption, and the surplus steam drives the turbine to generate electricity. The simulation of the turbine part uses the Compressor module. The turbine efficiency is set at 75 %, and the generator mechanical efficiency at 97 %. The superheated steam enters the intermediate-pressure turbine stage, expands to a pressure of 450 psia, then enters the low-pressure turbine, and expands to 35 psia. Finally, the steam enters the condensing turbine and expands to 1.5 psia [51,52].

2.3. Energy analysis

Due to the diversity of products, this paper primarily focuses on five indicators for energy analysis: the yield of aviation fuel ($Y_{products}$), the energy conversion rate of aviation fuel (α), the energy conversion rate of fuel (β), the energy efficiency of the system (η), and the carbon efficiency (α_C). These indicators are derived from well-established methodologies in the literature and provide a comprehensive framework for evaluating the performance metrics of our system [2,53]. The formulas for these calculations are as follows:

Table 2
Distribution of olefin oligomerization products.

Carbon Number	Proportion (wt%)
C_{5-}	3.79
C_5-C_7	13.6
C_8-C_{16}	71.23
C_{16+}	11.38

$$Y_{products} = \frac{m_{products}}{m_{bio}} \tag{4}$$

$$\alpha = \frac{E_{jet}}{E_{input}} \tag{5}$$

$$\beta = \frac{E_{fuel}}{E_{input}} \tag{6}$$

$$\eta = \frac{E_{fuel} + E_{electricity}}{E_{input}} \tag{7}$$

$$\beta_C = \frac{C_{fuel}}{C_{bio}} \tag{8}$$

Where $m_{products}$ fuel is the mass of fuel produced, kg/h; m_{bio} is the mass of the biomass input, kg/h; E_{jet} refers to the energy of the aviation fuel produced by the system, MJ/h; E_{input} represents the energy input into the system, which includes the energy of the biomass as well as electrical and thermal energy, MJ/h; E_{fuel} refers to the energy of the fuel produced by the system, MJ/h; C_{fuel} denotes the carbon content in the fuel produced by the system, mol/h; C_{bio} represents the carbon content in the biomass input into the system, mol/h.

2.4. Techno-economic analysis

In conducting the techno-economic analysis, the financial investment of the project is divided into two main components: capital investment and operating cost. Total capital investment (TCI) primarily includes three parts: fixed capital investment (FCI), working capital (WC), and land costs (LC). The prices of equipment and scale factors, installation factors refer to biomass gasification plants and other related research literature [48,51,54–57]. For equipment purchase and installation costs that cannot be found in the literature, the economic analysis module of Aspen Plus is referenced, and scale transformation formula is used to complete the conversion between different scales,as shown in Equation (9). In addition to scaling conversions, it is also necessary to standardize the equipment prices to the research year, with the calculation formula as shown in Equation (10). Equipment purchase and installation costs (*EPIC*) were calculated by converting the equipment purchase costs (*EPC*) using installation factors, as presented in Equation (11).

$$New\ Cost = Base\ Cost \left(\frac{New\ Size}{Base\ Size}\right)^n \tag{9}$$

$$Present\ Cost = Original\ Cost \left(\frac{PCI_P}{PCI_o}\right) \tag{10}$$

$$EPIC = k \cdot EPC \tag{11}$$

In the formula, n represents the equipment scale exponent, which generally ranges from 0.6 to 0.8; PCI_o refers to the plant cost index of the reference year; PCI_p denotes the plant cost index for the research year, which is specified as 525.4 in this article [50]; k represents the installation factor for the equipment.

After completing the calculation of equipment purchase costs, combine the equipment installation factor to calculate the purchase and installation costs of the equipment, and then further estimate the direct capital investment and other investment costs based on the calculation factors [44].

The operating cost mainly consists of variable production costs and fixed production costs. For variable production costs, feedstock consumption relies on Aspen Plus simulation results, and prices are primarily derived from literature research and various sales websites. For fixed production costs, the number of workers is set as follows, referring to literature [51]: The factory has 1 senior manager, 2 engineers, and 10 various managers (including laboratory and plant area personnel). Each workshop section is staffed with 3 senior technicians, 5 operators, 10 workers, and 6 clerical staff. Employee wages are calculated based on the average wages of various employees in the electricity and chemical industries published by the National Bureau of Statistics of China. Other costs are estimated based on relevant estimation factors, which are mainly referenced from technical and economic reports of similar factories [44].

Capital investment and cost accounting, while providing a certain reference for the economic viability of a project, cannot accurately measure the economic feasibility of the factory and the profitability of the product under the influence of one or more market economic factors. Discounted cash flow analysis can make up for the above shortcomings. The discounted cash flow method refers to the process of converting the expected cash flows of a company over a specific future period into their present value. The main evaluation indicator is the net present value (NPV) of the factory, which represents the difference between the future cash flows generated by the project investment and the investment itself, discounted at a certain benchmark discount rate i_0. The calculation formula is shown in equation (11). When NPV >0, it indicates that the project is economically feasible, and the larger the NPV, the stronger the project's profitability; when NPV <0, it indicates that the project is in a loss state throughout its entire life cycle. When NPV = 0, it indicates that the project is exactly at the break-even point, and the corresponding fuel selling price is the minimum fuel selling price (MFSP) [58].

$$NPV = \sum_{t=0}^{n} (CI_t - CO_t)(1+i_0)^{-t} = \sum_{t=0}^{n} CF_t(1+i_0)^{-t} \tag{11}$$

In the formula, CI_t represents the cash inflow in year t; CO_t represents the cash outflow in year t; i_0 is the benchmark discount rate; CF_t is the net cash flow in year t; n is the project's lifespan in years.

In this paper, when conducting discounted cash flow analysis, the benchmark discount rate is set at 10 %, the income tax rate is 25 % according to relevant regulations, and the commercial loan interest rate is 4.9 %. The capacity was set at 2000 dry metric tonnes of biomass per day, based on relevant literature [59]. The project's lifespan is 30 years, including a 3-year construction period and a 6-month start-up period, during which the product revenue is 50 % of the original, the variable operating costs are 75 %, and the fixed operating costs remain unchanged [51]. The project is financed by 40 %. The elements of the discounted cash flow analysis presented in Table A5 are derived from the report by the U.S. National Renewable Energy Laboratory (NREL) [49].

3. Results and discussion

3.1. Operating conditions optimization

The final liquid products produced are categorized into three types based on their carbon number distribution: gasoline (C_5-C_7), jet fuel (C_8-C_{16}), and diesel (C_{16+}). By adjusting the S/B and temperature during gasification, we can explore the impact of different gasification conditions on the yield of three products and the energy efficiency of the system. This analysis helps in optimizing the gasification operating conditions.

Firstly, the gasification temperature is set at 800 °C, and the S/B in the gasification process is set sequentially within the range of 0.1–0.9. The impact of S/B on the yield of the three products is shown in Fig. 3a, and the syngas composition distribution is shown in Fig. 3b.

As S/B increases, the product yield initially rises and then decreases. When S/B increases from 0.1 to 0.3, there is a significant improvement in yield. However, when S/B exceeds 0.5, the yield slightly declines, though not significantly. Based on the syngas composition distribution, it can be observed that when S/B is low, the H_2/CO ratio is small. To meet the requirements for olefin production, a large amount of CO is converted to CO_2 during the syngas adjustment phase, resulting in lower product yields. As shown in Fig. 2b, with the amount of steam increases, the proportion of CO in the syngas decreases while the proportion of CO_2 increases, which ultimately reduces the product yield. In conclusion, the optimal product yield is achieved at an S/B of 0.5.

With an S/B ratio of 0.5, the gasification temperature is sequentially set within the range of 700–950 °C to investigate the impact of gasification temperature on product yield and energy efficiency-related metrics. The results are shown in Fig. 4. The results indicate that as the gasification temperature increases, the yield of CO increases, and the H_2/CO ratio decreases. To meet the requirements for olefin production from syngas, CO is converted to CO_2 during the syngas adjustment phase, so the increase in product yield is not significant. As the gasification temperature rises, the yield of fuel increases slightly, but the energy consumption of the gasification process also increases. When the gasification temperature exceeds 850 °C, the system cannot achieve self-sufficiency in energy and requires additional energy input. When the biomass feed rate is 1000 kg/h, the energy consumption for the gasification process at a temperature of 900 °C is 199.94 MJ/h higher than

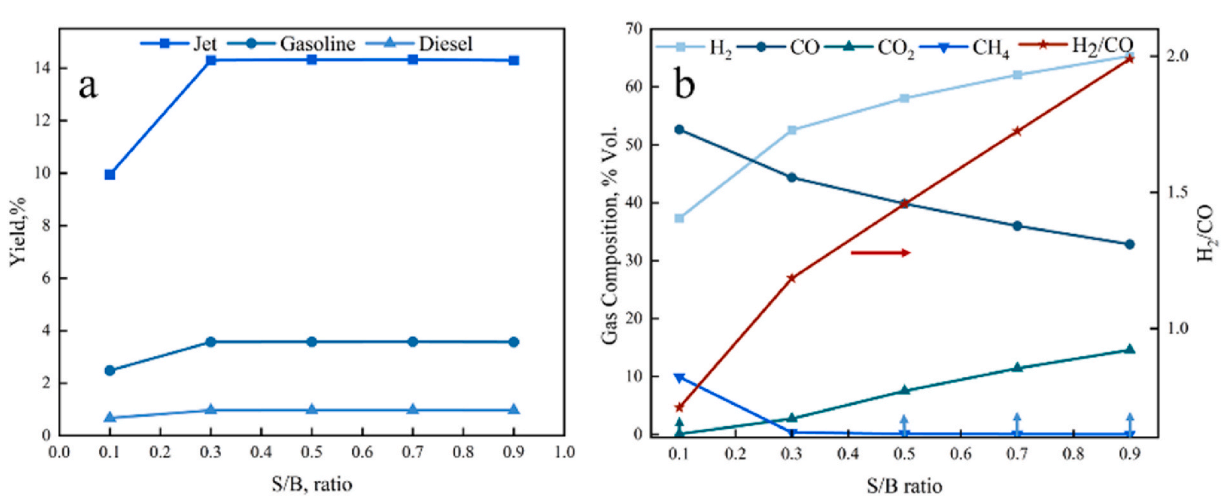


Fig. 3. Impact of S/B on system performance (a. product yield b. syngas composition).

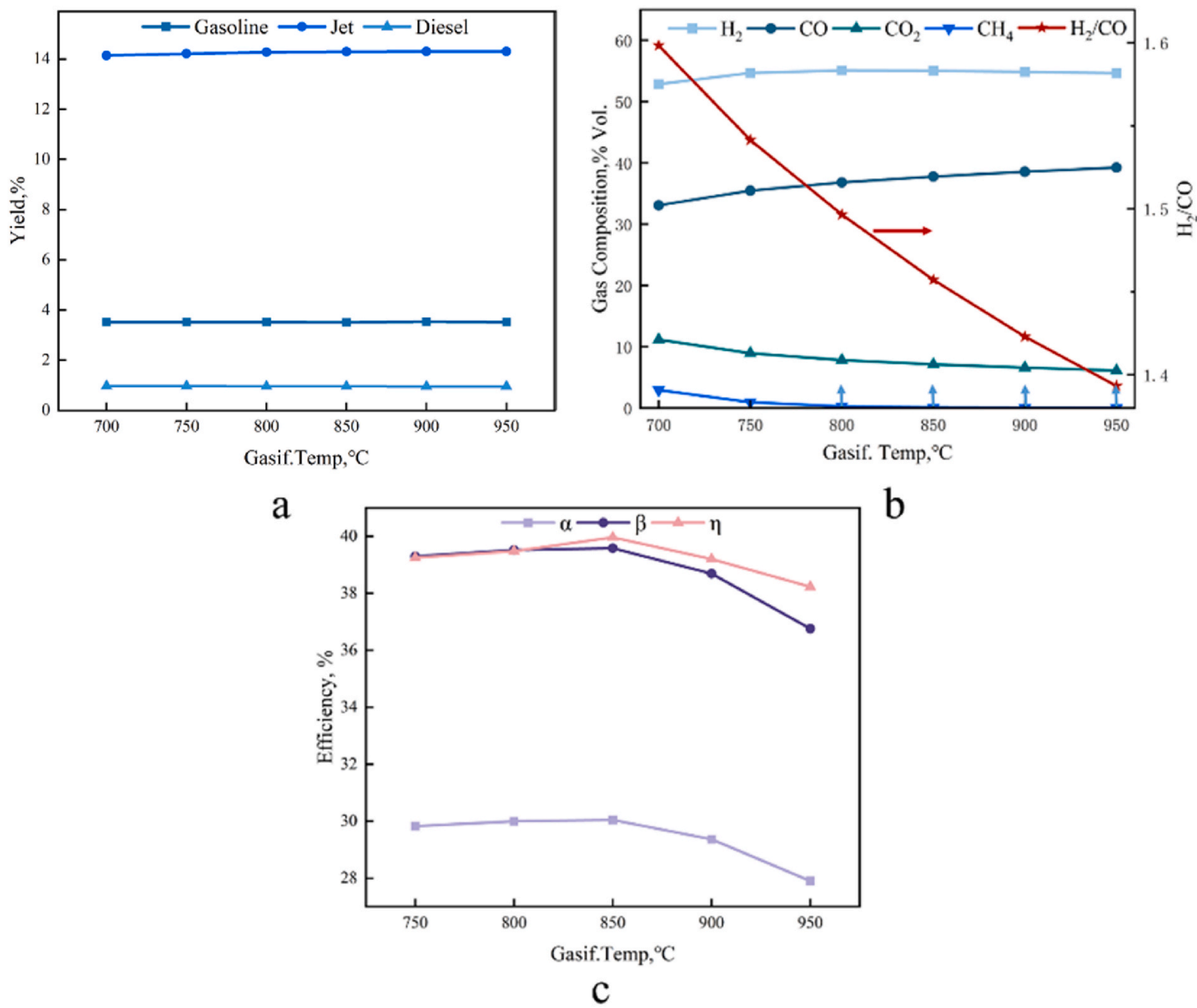


Fig. 4. Impact of gasification temperature on system performance (a. yield; b. syngas composition; c. energy-related efficiency).

that at 850 °C. Similarly, at a gasification temperature of 950 °C, the energy consumption is 390.46 MJ/h higher than at 850 °C. This causes a decline in the energy efficiency of the system once the temperature exceeds 850 °C. In summary, the optimal conditions for the gasification process are a temperature of 850 °C and an S/B ratio of 0.5. Therefore, all subsequent analyses were conducted under these conditions.

3.2. Energy analysis results

This study focuses on the energy analysis of GOO system to convert poplar or corn stover into green aviation fuel. By evaluating the energy inputs and outputs throughout the production process, we aim to assess the overall efficiency and sustainability of this innovative approach. The following sections detail the findings of our energy analysis,

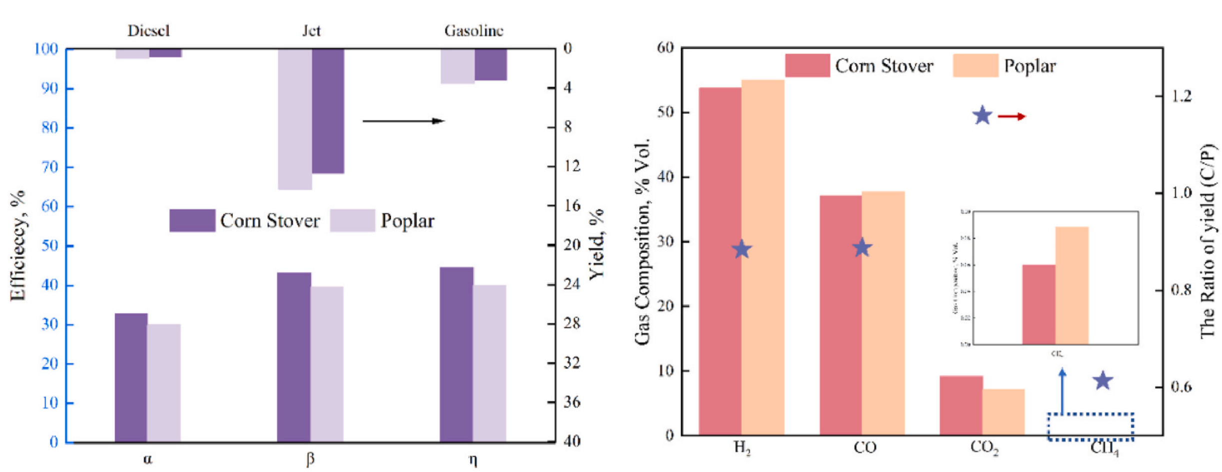


Fig. 5. Comparison of product yield, syngas composition distribution, and energy efficiency between CS-AF and P-AF scenarios.

highlighting key areas of energy consumption and potential improvements.

3.2.1. Energy efficiency

The product yield, syngas composition distribution, and related energy metrics for the two scenarios are shown in Fig. 5 and Table 3. It can be observed that compared to corn stover, poplar gasification results in higher yields of H_2 and CO, and a lower yield of CO_2. Consequently, the product yield in the corn stover-to-aviation fuel (CS-AF) scenario is lower than that in the poplar-to-aviation fuel (P-AF) scenario. However, since the calorific value of corn stover is 18 % lower than that of poplar, the energy efficiencies in the CS-AF scenario are 2–4 % higher than those in the P-AF scenario. Improved yield of aviation fuel often results in a higher energy efficiency, as more of the input energy is converted into useable fuel rather than being lost as waste. Therefore, subsequent technical optimizations could further enhance the capacity for aviation fuel production.

In existing studies, the yield of aviation fuel from corn stover systems ranges from 10.77 % to 11.82 %, which is 6.71 %–15.00 % lower than that in the CS-AF scenario of this study. The β ranges from 26.0 % to 32.75 % [31,32], which is 24.50 %–40.06 % lower than that in the CS-AF scenario of this study. This indicates that this study has made some progress in improving the yield and energy efficiency of biomass conversion to aviation fuel, highlighting the potential of biomass as a renewable energy source for the production of liquid fuels.

3.2.2. Carbon efficiency

The carbon efficiency for the CS-AF and P-AF scenarios was calculated separately, and the results are shown in Fig. 6. Analysis indicates that the carbon efficiency of the CS-AF scenario is 1.42 % lower than that of the P-AF scenario. According to the comparison of syngas composition distribution in Fig. 4, the yield of CO in the P-AF scenario is higher than that in the CS-AF scenario, resulting in a greater retention of carbon in the products for the P-AF scenario.

Although the CS-AF and P-AF scenarios utilize different feedstocks, they have the same process flow, and the primary stages responsible for carbon loss are identical. Therefore, to further analyze the main stages causing carbon loss in the system, a more detailed carbon flow analysis was conducted based on the P-AF scenario, as shown in Fig. 7. The carbon flow table is presented in Table A6. The main carbon loss in the system occurs during the syngas-to-olefins stage, where 37.78 % of the carbon is lost in the form of CO_2. This is primarily due to side reactions occurring during the conversion of syngas to olefins and the limited conversion rate of CO. The generation of CO_2 during the gasification and syngas conditioning processes results in a carbon loss of 30.63 %. Therefore, optimizing the syngas-to-olefins process, increasing the CO conversion rate, and suppressing side reactions are the main directions for further improving the carbon efficiency of system.

3.2.3. Influence of biomass characteristics on energy efficiency and yield

In this study, we selected corn stover and poplar as representative biomass types, where corn stover represents agricultural waste and poplar represents forestry waste. These two types of biomass provide a relevant comparison due to their distinct properties and availability.

The elemental composition of biomass is a critical factor affecting its energy content and gasification efficiency. The higher carbon content (52.4 %) in poplar contributes to a greater yield of H_2 and CO during the gasification process, which are essential for subsequent olefins synthesis and oligomerization. Conversely, the slightly lower carbon content (50.3 %) in corn stover results in a lower yield of syngas, impacting the overall efficiency of the conversion process.

Table 3
Comparison of energy efficiency between CS-AF and P-AF scenarios.

	α	β	η
CS-AF	32.69 %	43.38 %	44.48 %
P-PF	30.05 %	39.67 %	39.96 %

Moreover, the volatile matter and ash content of biomass are important parameters that influence the gasification process. The volatile matter content of poplar wood is 86.0 %, while that of corn stover is 70.4 %. The higher volatile matter content in poplar enables more efficient gasification, thereby yielding a higher syngas production. In comparison, the ash content of poplar wood is 1.6 %, whereas corn stover has an ash content of 6.0 %. The elevated ash content in corn stover can lead to operational challenges, such as increased slagging and reduced gasification efficiency.

In summary, the characteristics of biomass, including chemical composition, volatile matter content and ash content, significantly influence the energy efficiency and yield of bio-based aviation fuel production. A thorough understanding of these factors is crucial for optimizing the conversion process and enhancing the economic viability of bio-aviation fuel.

In conclusion, the energy efficiency of converting CS-AF into fuel is 43.38 %, with a carbon efficiency of 30 %. For P-AF, the energy efficiency of conversion into fuel is 39.67 %, and the carbon efficiency is 31.42 %. Based on the energy analysis of both CS-AF and P-AF scenarios, several recommendations have been made to enhance the efficiency and sustainability of biomass conversion into aviation fuel. First, optimizing the gasification processes, particularly the syngas-to-olefins conversion stage, is crucial for reducing carbon losses and improving overall carbon retention. Additionally, selecting biomass with higher carbon content and lower ash content, such as poplar, can lead to better performance in fuel production. Implementing pre-treatment processes to reduce the ash content of biomass can further mitigate operational challenges and enhance gasification efficiency. Overall, these strategies highlight the importance of continuous improvement and innovation in biomass conversion technologies to promote sustainable aviation fuel production.

3.3. Techno-economic analysis results of the biomass GOO system

In this study, we conducted an in-depth techno-economic analysis of a green aviation fuel GOO production plant using poplar or corn stover as feedstocks, to assess the economic feasibility and potential economic benefits of this sustainable aviation fuel production. The specific analysis results are as follows.

3.3.1. Capital investment

The scale factors, installation factors, as well as equipment purchase and installation costs of the main equipment in the GOO production plant are presented in Table A7. Other detailed calculation factors for capital investment refer to the economic and technical report on biomass gasification plants published by NREL [44]. The final calculation results are shown in Table A8. The EPIC for the biomass GOO to aviation fuel production plant amount to 341 million dollars (MD), whereas other literature on biomass gasification for liquid fuel production reports this value to be between 200 and 296 MD [49,59]. The total capital investment is 609 MD, compared to capital investments reported in similar study, which is 516 MD [59]. Given that the capital investment in this study is relatively close to the values found in comparable literature, the estimation of capital investment for the gasification to aviation fuel plant in this paper is within a reasonable range.

The proportion of each part in the capital investment is shown in Fig. 8. In terms of equipment-related investment, the olefin production & polymerization section contributes the most to the capital investment, accounting for nearly one-third of the total capital investment. To maintain a stable reaction temperature during the conversion of syngas to olefins, it is essential to install heat exchange water pipes around the reactor, resulting in increased costs for the olefins production unit. Furthermore, the incorporation of multiple separation towers in the olefins separation process further elevates the equipment acquisition

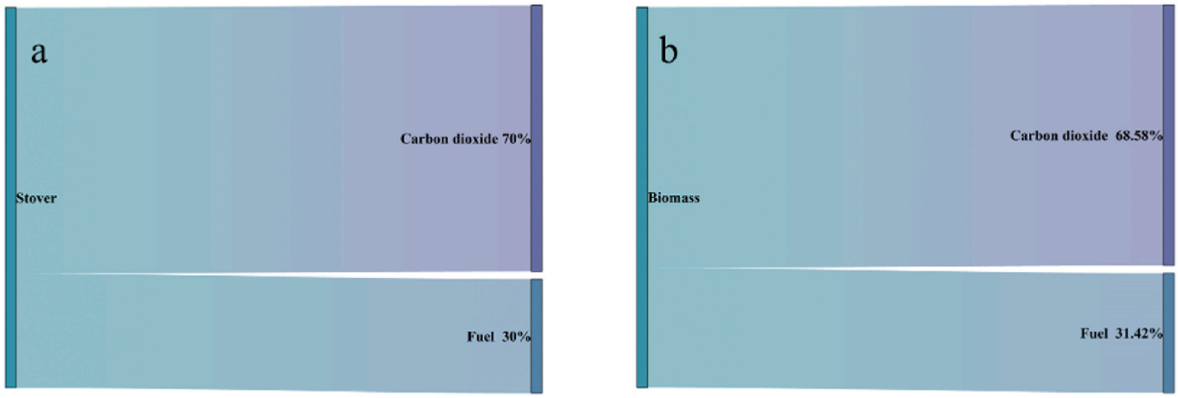


Fig. 6. Comparison of carbon efficiency between S-AF and P-AF (a. S-AF; b. P-AF).

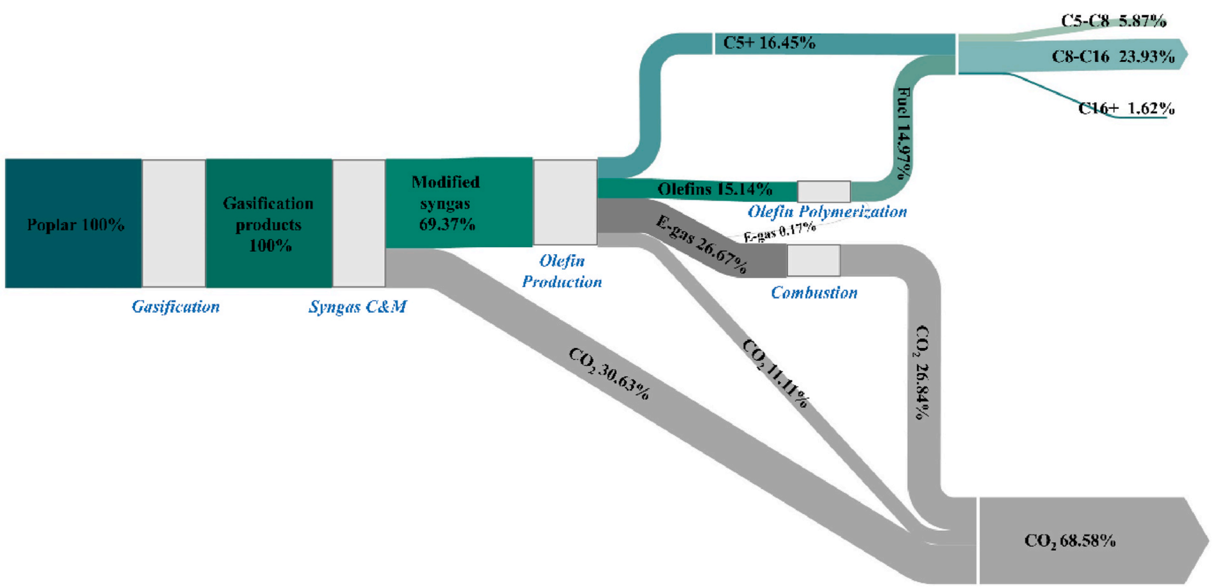


Fig. 7. Carbon flow diagram of the system under the P-AF scenario.

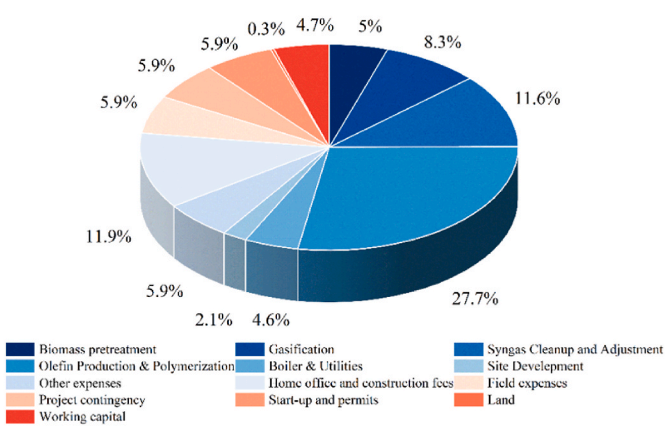


Fig. 8. Proportion of capital investment in various parts of the GOO plant.

costs for this section [55]. The syngas cleanup and gasification sections also account for a relatively high proportion of the total factory capital investment, reaching 11.6 % and 8.3 %, respectively. The complex syngas cleanup process increases equipment investment. Therefore, optimizing the gasification process and reducing the production of gas impurities will effectively reduce the equipment investment in the syngas cleanup and adjustment section, thereby lowering the capital investment. The steam demand of the gasification plant is low, and the equipment investment in the entire boiler & utilities system is mainly for waste heat recovery devices, so the proportion of capital investment in this part is not high, only 4.6 %. In addition to equipment investment, home office and construction fees accounts for 11.9 % of the total capital investment, while the rest of the indirect capital investment accounts for about 5–6 %. In summary, optimizing the olefins separation process and the gasification process, and reducing the investment in separation equipment and syngas cleanup equipment, are important directions for reducing the capital investment in biomass gasification to aviation fuel production plants in the future.

3.3.2. Operating cost

The calculation of aviation fuel production costs was carried out for two schemes, CS-AF and P-AF, respectively. The results of the calculations are shown in Table A9, and the proportion of each part involved in the production of 1t fuel is illustrated in Fig. 9. In this context, by-product credits refer to the revenue generated from the sale of electricity, which effectively offsets certain production costs associated with aviation fuel.

The aviation fuel production costs for the CS-AF and P-AF schemes are $1235.0/t and $878.7/t, respectively. The higher price of corn stover and the lower aviation fuel yield in the CS-AF scheme are the reasons

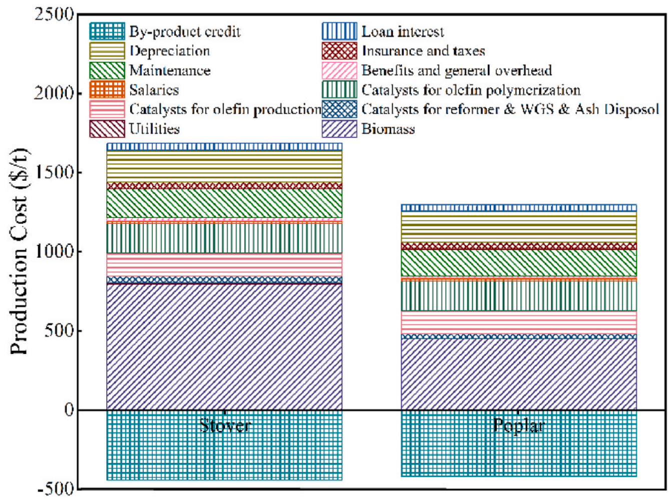


Fig. 9. Comparison of production costs for CS-AF and P-AF.

for this phenomenon. In both schemes, the variable costs account for a high proportion of the total production costs, reaching 69 % and63 %, respectively. In the entire biomass gasification conversion process, there are no additional material inputs besides the feedstocks and catalysts, which leads to the feedstocks contributing more than 50 % to the variable costs in both schemes. Therefore, the selection of feedstocks has a significant impact on the production costs of gasification aviation fuel. Moreover, in both schemes, the fixed production costs account for more than 35 % of the total production costs, making the high fixed production costs a major factor limiting the economic viability of the gasification route.

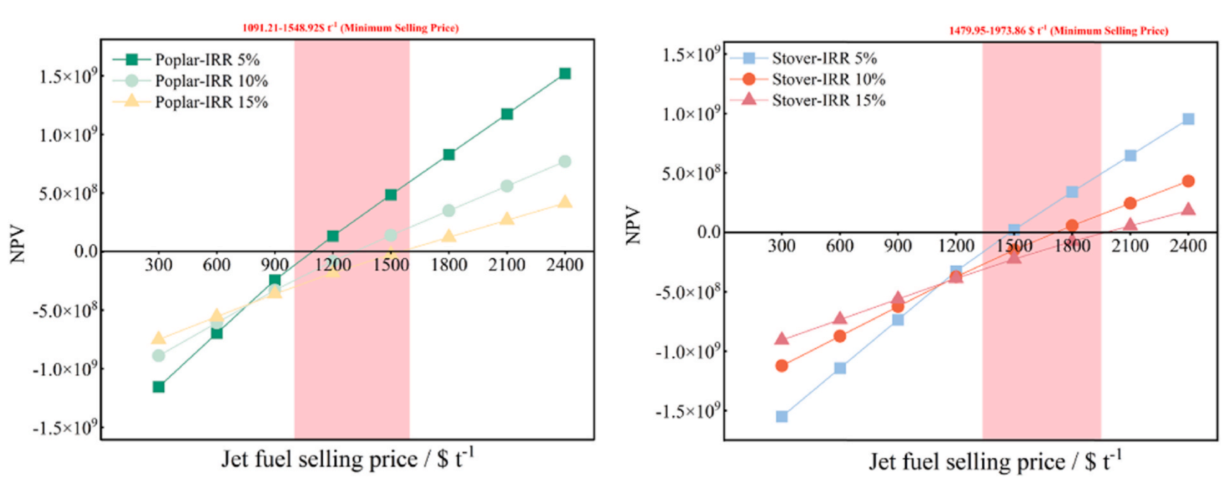
3.3.3. Minimum fuel selling price

Conduct a discounted cash flow analysis for the CS-AF and P-AF schemes, calculate the MFSP for aviation fuel under both schemes, and explore the relationship between fuel prices and the NPV of the plant under different internal rates of return. The results are shown in Fig. 10. It can be seen that the MFSP for aviation fuel under the CS-AF and P-AF schemes are $1713.58/t and $1307.77/t, respectively. The former is 31.03 % higher than the latter, and the difference in operating costs due to different feedstock prices is the main reason for the significant difference in the MFSP of aviation fuel under the two schemes. When the IRR varies from 5 % to 15 %, the change rate of the MFSP for CS-AF aviation fuel is 25 %, while for the P-AF scheme, it is 41.9 %. Under the P-AF scheme, the proportion of fixed production costs in the aviation fuel production cost is higher, hence its response to changes in the IRR is more pronounced than the CS-AF scheme. The selection of different feedstocks will affect the economic viability of the plant from multiple aspects. The gasification process is not very selective in terms of feedstock choice in production technology, so choosing feedstocks that are relatively cheaper can improve the economic viability of the entire plant while ensuring yield.

Currently, economic analyses of biomass GOO systems have not been conducted. To underscore the significance of the results, a comparative evaluation was performed on the MFSP of other fuel products derived from corn stover and poplar. The findings are presented in Table 4. It can be observed that the technology for producing alcohols from corn stover via fermentation has become relatively mature. Specifically, the MFSP of ethanol ranges from $1723.53/tge to $1986.97/tge, which is $9.95/tge to $273.39/tge higher than the MFSP of aviation fuel in this study. The use of corn and sugarcane as feedstocks for fermentation can enhance the economic viability, with the MFSP ranging from $1237.76/tge to $1260.41/tge. Furthermore, the MFSP of butanol is $143.15/tge lower than that of the aviation fuel in this study. However, compared to alcohols, the hydrocarbons produced in this study have higher energy density, more stable combustion performance, and greater compatibility with existing fuels, thus offering certain advantages. For poplar, current technological pathways are more diverse, including fermentation, gasification, fermentation coupled with gasification and fast pyrolysis upgrading. The product prices range from $1416.25/tge to $2180.69/tge, which is 8.30 %–66.75 % higher than the $1307.77/tge for aviation fuel in this study, indicating that the results of this study are competitive.

3.3.4. The impact of scale on relevant economic indicators

For the P-AF scheme, the impact of scale on economic indicators is explored as the scale varies from 800 t/d to 2000 t/d, with the results shown in Fig. 11. As the capacity increases, the proportion of fixed production costs and fixed capital investment decreases, while the share of variable production costs becomes more significant. As the scale increases from 800 t/d to 2000 t/d, the production cost of aviation fuel decreases by 17 %, and the MFSP decreases by 21.47 %. The fixed production costs of gasification aviation fuel account for a high proportion of the total production costs, hence the economic viability is strongly influenced by scale. Fig. 11a reflects the impact of different scales on the proportion of each part of the production costs. When the scale is greater than 1200 t/d, the proportion of loan interest repayment



a b

Fig. 10. The Impact of IRR on NPV for the CS-AF and P-AF Schemes (a. P-AF; b. CS-AF).

Table 4
Economic comparison of different process pathways for producing liquid fuels from biomass.

Feedstock	Pathway	Product	MFSP	Reference
Corn stover	Gasification, olefins synthesis & oligomerization	Aviation fuel	$1713.58/t	This paper
Corn stover	Fermentation	Ethanol	$1723.53/tge	[60]
Corn stover	Fermentation	Ethanol	$1124.14/t $1831.53/tge	[61]
Corn stover	Fermentation	Butanol	$1321.33/t $1468.14/tge	[62]
Corn stover	Fermentation	Ethanol	$1986.97/tge	[63]
Corn and sugarcane	Fermentation & saccharification	Ethanol	$761.72/t $1237.76/tge	[64]
Corn and sugarcane	Fermentation & dry grind	Ethanol	$775.66/t $1260.41/tge	[64]
Poplar	Gasification, olefins synthesis & oligomerization	Aviation fuel	$1307.77/t	This paper
Poplar	Fermentation	Ethanol	$1283/t $2082.79/tge	[64]
Poplar	Fermentation & lignin gasification fermentation	Ethanol	$1342/t $2178.57/tge	[64]
Poplar	Fast pyrolysis & upgrading	Aviation fuel	$1416.25/t	[65]
Poplar	gasification	Ethanol	$1139.67/t $1709.51/tge	[66]

*/tge stands for/t of gasoline equivalent.

and management fees within the fixed costs remains essentially unchanged. Therefore, to enhance the advantages of scale effects on the economic viability of gasification plants, the design of such plants should be greater than 1200 t/d.

3.3.5. *Sensitivity analysis*

In order to investigate the key factors affecting the economic viability of the biomass gasification plant for the production of aviation fuel, and to reduce the uncertainty caused by fluctuations in the prices of related materials, sensitivity analysis is conducted on financial analysis factors such as capital investment, loan interest rates, and income tax rates, operational factors of the plant such as operating time and aviation fuel yield, and material price factors such as feedstock prices and catalyst prices. The variation rates for each indicator are set at ±15 %. The changes in the MFSP for aviation fuel under the CS-AF and P-AF schemes are shown in Fig. 12. In this context, a positive impact refers to situations where changes in the indicators lead to a decrease in the MFSP, while a negative impact refers to situations where changes in the indicators result in an increase in the MFSP.

From the perspective of plant operation-related factors, for the CS-AF scheme, when the aviation fuel yield and plant operating hours change by 15 %, the MFSP variation rates are above 13 % and 7 %, respectively. The P-AF scheme has a higher product yield than the CS-AF scheme, thus it is more sensitive to operating time. Regarding material price-related factors, the MFSP is most sensitive to the feedstocks, with variation rates of approximately 7 % for the CS-AF scheme and 5 % for the P-AF scheme. Looking at financial-related factors, the MFSP is most sensitive to the FCI, with variation rates reaching 8 % for the CS-AF scheme and 9 % for the P-AF scheme. The main reasons for the differences between the two schemes are twofold: firstly, the P-AF scheme has a lower proportion of variable costs, and secondly, the P-AF scheme has a higher product yield. Apart from the IRR, which affects the MFSP by about 5 %, the impact of other financial indicators is around 1 %. Overall, the MFSP is most sensitive to the aviation fuel yield; a higher yield of aviation fuel results in a lower MFSP, as the fixed costs of production are spread over a larger quantity of fuel. Therefore, maximizing yield is a key strategy for reducing the overall cost of aviation fuel. Additionally, the sensitivity of gasification plants to financial factors is strong, which suggests that high capital investment is also a significant factor limiting the economic viability of gasification plants.

4. Conclusion

This paper has designed and simulated the biomass GOO process for the production of aviation fuel based on Aspen Plus. It has conducted both an energy analysis and an economic evaluation, comparing two types of feedstocks, poplar and corn stover. The main conclusions are as follows.

(1) This paper, integrating real-world data from the entire process, has designed and constructed a simulation model for a novel high-selectivity preparation process of aviation fuel through

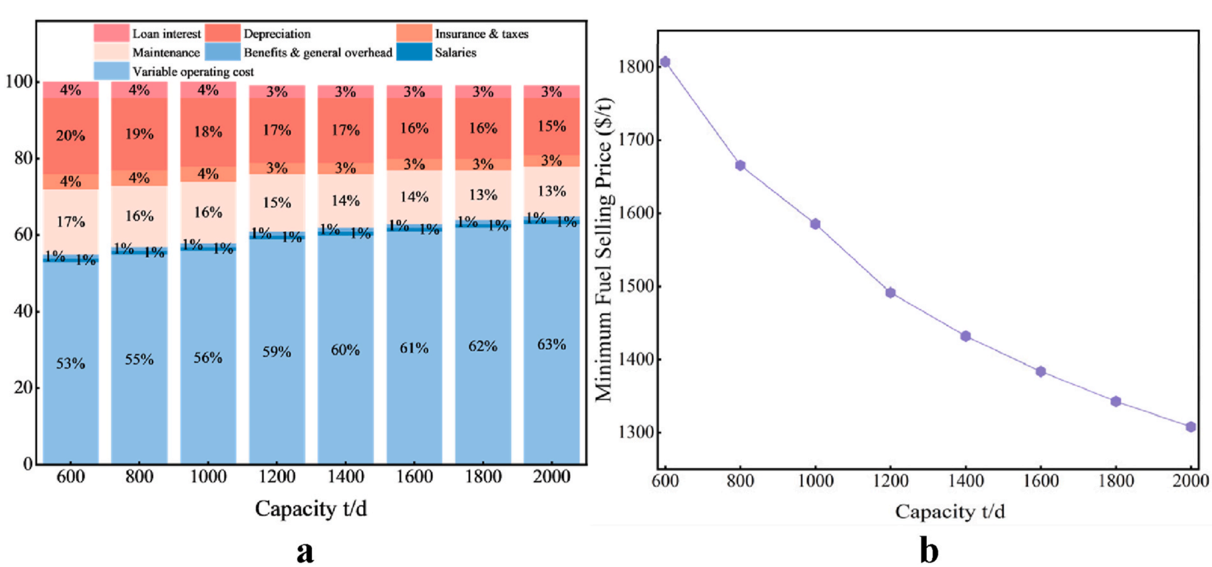


Fig. 11. The impact of scale on economic indicators of the GOO plant (a. proportions of various production costs; b. MFSP).

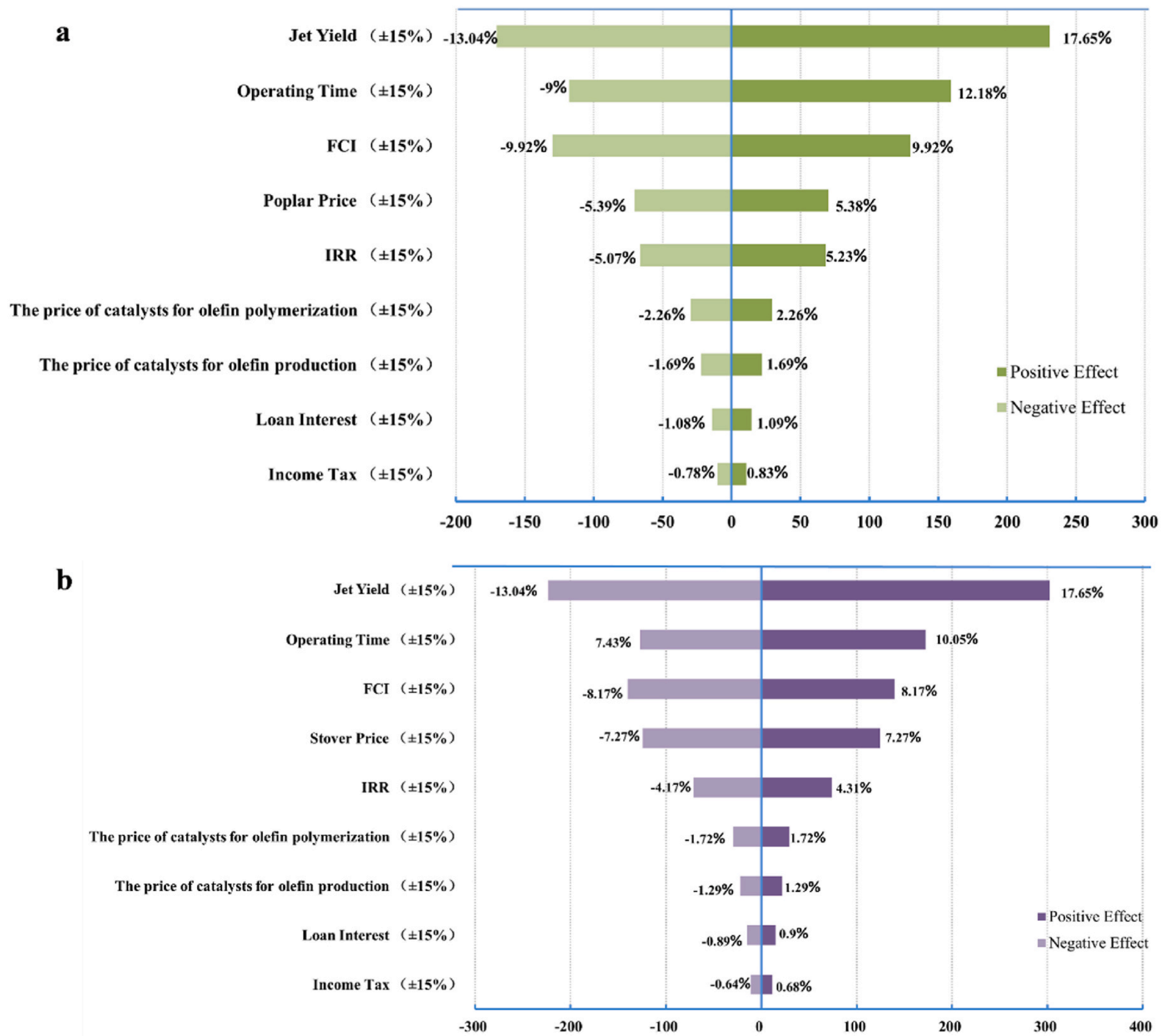


Fig. 12. Sensitivity analysis of aviation fuel MFSP (a. P-AF; b. CS-AF) Jet Yield.

biomass GOO. The key parameters in the process have been compared with experimental results, thereby proving the reliability of the model and providing favorable support for subsequent energy and economic analysis.

(2) The optimization of the two key operating conditions in the gasification process, gasification temperature and S/B ratio, indicates that the optimal conditions are 850 °C and S/B = 0.5. Under these optimal conditions, the CS-AF and P-AF scenarios achieve energy conversion efficiencies of 32.69 % and 30.05 %, energy efficiencies of 44.5 % and 39.96 %, and carbon efficiencies of 30 % and 31.42 %, respectively. Since poplar has a higher calorific value than corn stover, although the P-AF scenario has a higher product yield and carbon efficiency, its energy efficiency is lower than that of the CS-AF scenario.

(3) Optimizing the gasification processes, particularly the syngas-to-olefins conversion stage, is crucial for reducing carbon losses and improving overall carbon retention. Additionally, selecting biomass with higher carbon content and lower ash content, can lead to better performance in fuel production. Implementing pretreatment processes to reduce the ash content of biomass can further enhance gasification efficiency.

(4) The capital investment for the biomass GOO plant reaches 609 MD due to the high equipment costs associated with purification and the olefin separation process. The production costs for aviation fuel in the CS-AF and P-AF schemes are $1235.0/t and $878.7/t, respectively. The MFSP for aviation fuel is $1713.58/t in the CS-AF scheme and $1307.77/t in the P-AF scheme. The primary factor contributing to the significant price disparity between the two schemes is the difference in feedstock costs.

(5) The MFSP is most sensitive to the aviation fuel yield, hence, optimizing technology to increase yield remains key to further improving the economic viability of the gasification plant. Additionally, to mitigate the impact of scale effects, the scale of the gasification plant should be greater than 1200 t/d.

In summary, from the production process perspective, the gasification route is not highly selective towards feedstock types, allowing for the conversion of different types of feedstocks into aviation fuel without altering the process flow. However, the price of the feedstock significantly impacts the economic performance of the gasification route. Therefore, selecting feedstock with a lower price can enhance the economic viability and sustainability of the entire plant while ensuring yield. In the future, with continuous technological advancements and further cost reductions, bio-aviation fuel is expected to be a key pathway for reducing carbon emissions in aviation, thereby making a positive contribution to achieving global carbon neutrality goals.

Nomenclature

CS-AF	Corn Stover-to-aviation Fuel	EPC	Equipment purchase costs
FCI	Fixed Capital Investment	F-T	Fischer-Tropsch
LC	Land Costs	MD	Million Dollars
MFSP	Minimum Fuel Selling Prices	NPV	Net Present Value
P-AF	Poplar-to-aviation Fuel	S/B	Steam-to-biomass Ratio
TCI	Total Capital Investment	WC	Working Capital
WGS	Water-gas Shift		
EPIC	Equipment purchase and installation costs		
GOO	Gasification, Olefins Synthesis and Oligomerization		

CRediT authorship contribution statement

Qi Wei: Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **Zhongyang Luo:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Haoran Sun:** Investigation, Data curation. **Qian Qian:** Visualization, Investigation. **Jingkang Shi:** Supervision, Resources. **Caixia Song:** Visualization, Validation. **Evgeny R. Naranov:** Writing – review & editing, Validation.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2025.136736.

Data availability

Data will be made available on request.

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