From Municipal Solid Waste to Sustainable Aviation Fuel: Process Design

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Abstract

The aviation industry has rebounded post-pandemic, where carbon dioxide (CO2) emissions escalated to 80% of pre-pandemic levels. Studies on waste-to-energy have been exploring various methods like catalytic hydro-processing, pyrolysis of waste plastic, and gasification coupled with Fischer–Tropsch processes. In this work, Aspen Plus was utilized to model a waste-based system, aiming to showcase the production of bio-jet fuel from municipal solid waste (MSW), treated wastewater and captured CO2. The system involved steam gasification, Fischer-Tropsch synthesis, dry reforming, hydrocracking, and isomerization processes. The results demonstrated the product distribution after each stage, emphasizing the potential of producing jet fuel with the highest selectivity of 53.3% and a total production of 357,781 tonnes/year out of 3 million tonnes of MSW. Such initiatives presented a promising pathway to mitigate aviation emissions while harnessing waste as a valuable resource for energy production.

**Keywords**: Bio-jet fuel, Sustainable aviation, Sustainable jet fuel, waste-to-energy

1. Introduction

The aviation industry accounted for 2.5% of the global carbon dioxide (CO2) emissions (Ritchie, 2020). As aviation's demand recovered in 2022, post-pandemic, the emissions rebounded to nearly 80% of pre-pandemic levels, reaching 800 million metric tons of CO2 (IEA, 2023). Meanwhile, the world's rapid industrial progress boosted the economy but also led to the emission of diverse pollutants into the environment, stemming from various industries. These pollutants have seeped into the soil and groundwater, posing a threat due to improper treatment of industrial effluents and solid wastes discharged into the surroundings (Verma & Sharma, 2023). Currently, the world has been generating 2.01 billion tonnes of municipal solid waste (MSW) annually, with a minimum of 33% of waste not being managed in an environmentally safe manner. The average daily waste produced per person globally used to be 0.74 kg, but the range varied significantly, from 0.11 to 4.54 kg. By 2050, global waste is expected to grow to 3.40 billion tonnes (The World Bank, 2023). The utilization of waste for energy production holds a significant importance in meeting future global energy needs.

* + 1. Sustainable aviation and alternative jet fuels from waste

Producing sustainable aviation fuel from waste materials like MSW, encompassing food waste and waste cooking oils alongside agricultural and forestry residues, utilizing existing conversion technologies has been studied recently by Emmanouilidou et al. (2023). Their systematic review revealed that the catalytic hydro-processing of waste lipid feedstocks had been the most employed method for producing bio-jet fuel (BJF). Additionally, the catalytic pyrolysis of waste plastic and co-pyrolysis with solid biomass residues had the potential to contribute to effective policy support and enhance current technologies to reduce production costs. Moreover, the combination of gasification with Fischer–Tropsch (FT) processes emerged as an intriguing pathway for sustainable aviation fuel production. In this study, a completely waste-based processing pathway is evaluated, where all feeding streams are of a waste-nature. The system is based on gasification and Fischer-Tropsch processes, where the key feedstock is MSW, while treated sewage effluent is used as a gasifying agent, and captured CO2 is utilized within the process to run dry reforming of methane. The system is simulated and evaluated in Aspen Plus.

* 1. Methodology

Aspen Plus (V.12) ® was utilized to simulate the system for a Qatar case study, aiming to mainly generate BJF from various biomass sources, considering earlier modelling approaches (Alherbawi et al., 2023). Figure 1 illustrates the process flow of the system. The primary process involves integrating biomass gasification, followed by FT synthesis. Additionally, a dry-reforming phase employing CO2 was implemented to increase BJF production and decrease the environmental impact of the system. The system's design was based on assumptions of an isothermal system and steady-state reactions. Thermodynamic properties were estimated using the Redlich-Kwong-Soave (RK-SOAVE) and non-random two-liquid model (NRTL).



Figure 1: Flowsheet of a hybrid biorefinery.

MSW was used as a feedstock and was processed through gasification. 3 million tonnes of locally available MSW were simulated as an initial feed after the drying process, where a rotary dryer was modelled by an "RYield" block, operating at a temperature of 110°C. Table 1 shows the characteristics of the utilized feedstock. At first, Aspen Plus categorized all solid inputs as non-conventional elements based on their elemental and proximate attributes from Table 1. MSW in a dry state were fed into the gasifier. The outcomes of the drying phase were calculated using the proximate analysis of the inputs, redefining the dried remnants with a zero-moisture content.

Table 1: Attributes of MSW characteristics utilized in this study.

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| **Moisture (%)** | **Fixed carbon (%)** | **Volatile matter****(%)** | **Ash (%)** | **C****(%)** | **H****(%)** | **N****(%)** | **S****(%)** | **O****(%)** |
| 7.56 | 24.21 | 57.99 | 17.8 | 48.23 | 5.16 | 1.21 | 0.29 | 27.31 |

* + 1. Steam gasification

A steam gasifier was implemented at 1100°C with a steam-to-feed ratio of 1.2. A high steam input is considered to enhance the H2/CO ratio for optimal FT process. Local treated sewage effluent (TSE) is used as a gasifying agent, where it is treated locally to a high purity level, however, it is mostly unutilized due to public unacceptance. Decomposition was the initial step in breaking down biomass into simpler components, fulfilling equation 1, the process was simulated employing two successive units. The first unit was represented by an "RYield" block, converting unconventional components into conventional components like char, solid sulfur, hydrogen, nitrogen, and oxygen. The second unit, using an "RGibbs" block, aimed to convert volatile carbon into potential products (e.g., methane, carbon dioxide, carbon monoxide), while nitrogen and sulfur contents were transformed into ammonia and hydrogen sulfide, respectively, due to the considerable presence of hydrogen in the reaction medium. Subsequent oxidation processes occurred due to the presence of oxygen as an intermediate product from the breakdown stage at a high operating temperature. Key reactions were simulated based on Equations 5–8 using an "REquil" unit. The final phase of the gasification reactions was modelled utilizing an "RGibbs" block, which calculates phase and chemical equilibrium by minimizing the Gibbs free energy. The resulting gases throughout these stages included H2, CO, CO2, H2O, CH4, NH3, and H2S. However, it was expected that nearly all char content would be volatilized by the end of the reaction, while ash was discharged as waste at the end of the process. Eq. (1) to Eq. (10) were assumed to be the only processes occurring under the specified conditions to ensure model simplicity.

A two-phase flash separator was employed to dry the wet syngas. The optimal operating conditions of the flash unit were determined through automated sensitivity analysis, running at a high pressure of 40 bar. Wax generation is assumed to be negligible due to the high processing temperature. Crude syngas is then underwent purification to remove impurities (primarily CO2, NH3, and H2S) using the methanol absorption system, wherein these impurities were dissolved into chilled methanol at high pressure.

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| --- | --- |
| Pyrolysis: $Biomass \rightarrow Char + Tar + NH\_{3} +H\_{2}S + H\_{2} + CO +CO\_{2}$ |  (1) |
| Complete Char Combustion: $C + O\_{2}\rightarrow CO\_{2}$  |  (2) |
| Incomplete Char Combustion: $C + 0.5O\_{2} \rightarrow CO$ |  (3) |
| Steam production: $H\_{2}+ 0.5 O\_{2} \rightarrow H\_{2}O$  |  (4) |
| CO oxidation: $CO + 0.5O\_{2} \leftrightarrow \leftrightarrow CO\_{2}$ |  (5) |
| Boudouard reaction: $C+ CO\_{2} \leftrightarrow 2 CO$  |  (6) |
| Methanation: $C+ 2H\_{2} \leftrightarrow CH\_{4}$ |  (7) |
| Steam gasification: $C+ H\_{2}O \leftrightarrow CO+H\_{2}$  |  (8) |
| Methane reforming: $CH\_{4}+ H\_{2}O \leftrightarrow CO+3H\_{2}$  |  (9) |
| Water gas shift reaction: $CO+ H\_{2}O \leftrightarrow CO\_{2}+H\_{2}$  |  (10) |

* + 1. Fischer-Tropsch

A cobalt-based catalyst was selected due to its high stability. A slurry-phase reactor (SPR) using Co/Al2O3 catalyst is considered. The FT simulation began by introducing purified syngas into the FT reactor represented by an "RYield" block. The process occurred at 240 °C and 25 bar, predicting product distribution using a Fortran code based on the Anderson-Schulz-Flory (ASF) correlation (Schulz, 1999). For maximizing kerosene-range compounds, an α value of 0.85 was set, assuming an 80% CO conversion into paraffins, olefins, and alcohols (AlNouss et al., 2019). Around 50 chemical reaction equations were employed to predict hydrocarbon pathways leading to the occurrence of expected compounds.

* + 1. Dry Reforming, Hydrocracking and Isomerization

In this particular model, the integration of dry reforming within the system was implemented to enhance fuel production while mitigating the carbon dioxide produced. The simulation was conducted at 800°C, with a CO2/CH4 ratio of 5, using a Ni/Al2O3 catalyst. Dry reforming, being highly endothermic, demands a substantial amount of heat to drive the reaction. On the contrary, FT is notably exothermic. Consequently, after an initial energy analysis, it was observed that the heat released by FT was approximately equivalent to the heat required by the reforming unit. Thus, to minimize the overall energy demand, heat integration was carried out between the two units. To simulate the process, an "RStoic" block was employed, defining potential reactions with a fractional conversion of 95% (Jiang et al., 2013; Lavoie, 2014).

Hydrocracking and isomerization were employed to increase the selectivity of BJF production. In this study, hydrocracking reactions occurred at 350°C and 80 bar, using a zeolite catalyst at a specified rate. Additionally, to enhance the quality of BJF, the product required isomerization. This step aimed to alter the structure of branched paraffins, as they display lower freezing points and surface tension, positively impacting the final product. Isomerization was conducted separately using a platinum-alumina catalyst system at defined conditions. The product distribution from this process was determined through an experimental study (Dhar et al., 2017). Operating at specific temperature and pressure conditions, this process was essential to control the characteristics of the resulting products.

* + 1. Downstream Process

In the downstream process, the combined stream from various sub-units was passed through subsequent units to obtain different fuel categories. Initial processing involved a multi-stage flash drum to remove water and achieve gas-liquid separation. Higher hydrocarbons were then directed into a fractionation column with 18 stages to gather distinct fuel types, including BJF, gasoline, and diesel.

* 1. Results

The utilization of 3 million tonnes of MSW with the input of 3.6 million tonnes of TSE has led to the production of 3.96 and 0.5 million tonnes of gas and solids, respectively, per year, as per the ratio represented in Figure 2. In addition, the crude syngas composition is reflected in Figure 3. H2/CO ratio of 2.05 is achieved, which is optimal for FT process.

At FT and reforming stage, the obtained syncrude's composition is illustrated in Figure 4. Where at the selected operating conditions, jet fuel (C8-C16) dominated the fuel mixture, reducing the need for intensive cracking.

At the final stage of cracking, isomerization and distillation, 0.37 million tonnes of jet fuel are obtained (53.3% liquid fuel selectivity), followed by fuel gas (0.26 Mtonnes/year), gasoline (0.2 Mtonnes/year) and green diesel (0.13 Mtonnes/year) as represented in Figures 5 and 6.

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| Figure 2: Gasification's products distribution. | Figure 3: crude syngas composition. |
| A graph of a number of products  Description automatically generated with medium confidence Figure 4: FT products distribution. |
| Figure 5: Final liquid products selectivity. | Figure 6: Final products total yield. |

* 1. Conclusions

Post-pandemic aviation recovery led to a surge in emissions, emphasizing the urgency for sustainable practices. Waste-to-energy solutions, especially deriving aviation fuel from waste materials, offer promising environmental benefits. Research in waste-to-energy conversion methods like gasification highlights technical hurdles and avenues for improvement, aiming to refine technologies and reduce operational costs. The system for bio-jet fuel production from MSW illustrated here has shown the potential for generating environmentally friendly aviation fuel. The results exhibited product distributions, indicating the viability of producing substantial quantities of jet fuel from waste. Future expansion of this study may focus on evaluating the environmental and economic performance of the process in comparison to the conventional Jet-A and Jet-B fuels.

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