



# SAF MODULE

VOLUME 2

## 2. SAF Feedstocks and Production Pathways: Technologies, Classifications, and Comparative Insights

- Feedstocks for SAF Production
- Categorization of Feedstocks
- ASTM Approved SAF Production Pathways
- Comparative Analysis of Four Major Pathways
- Co-Processing Production Methods
- Pathways Under Evaluation



# Feedstocks for SAF Production

- Feedstocks are the **raw materials** used to produce sustainable aviation fuel
- Feedstocks are **chosen for their potential to reduce lifecycle greenhouse gas emissions**, and must meet sustainability criteria
- Both EU RED and ICAO CORSIA consider a **range of different feedstocks** and have differing approaches to the recognition of feedstocks under their respective frameworks



# Categorization of Feedstocks

- Under the CORSIA framework, feedstocks are broadly categorized into **five categories**:
  1. **Primary and Co-products:** These are the main products of a production process. These products have significant economic value and elastic supply
  2. **By-products:** These are secondary products with inelastic supply and economic value
  3. **Wastes:** These are materials with inelastic supply and no economic value. A waste is any substance or object which the holder discards or intends or is required to discard
  4. **Residues** are secondary materials with inelastic supply and little economic value
- Under the CORSIA framework, by-products, wastes, and residues are entitled to an **ILUC value of zero** on the calculation of the life cycle emission value of the SAF



# Feedstocks: Primary Products

| Feedstock                            | Classification                                                                        |                 |
|--------------------------------------|---------------------------------------------------------------------------------------|-----------------|
| Brassica carinata oilseed            |    | Primary product |
| Camelina oilseed                     |    | Primary product |
| Corn grain                           |    | Primary product |
| Jatropha oilseed                     |   | Primary product |
| Miscanthus (herbaceous energy crops) |  | Primary product |
| Palm fresh fruit bunches             |  | Primary product |
| Poplar (short-rotation woody crops)  |  | Primary product |
| Rapeseed oilseed                     |  | Primary product |

# Primary Products, Co-products, Wastes

| Feedstock                             | Classification                                                                        |                 |
|---------------------------------------|---------------------------------------------------------------------------------------|-----------------|
| Soybean oilseed                       |    | Primary product |
| Sugar beet                            |    | Primary product |
| Sugarcane                             |    | Primary product |
| Switchgrass (herbaceous energy crops) |   | Primary product |
| Molasses                              |  | Co-product      |
| Municipal solid waste (MSW)           |  | Waste           |
| Used cooking oil                      |  | Waste           |
| Waste gases                           |  | Waste           |

# Feedstocks: By-products

| Feedstock                  | Classification                                                                        |            |
|----------------------------|---------------------------------------------------------------------------------------|------------|
| Palm fatty acid distillate |    | By-product |
| Technical Corn oil         |    | By-product |
| Tallow                     |    | By-product |
| Beef Tallow                |   | By-product |
| Non-Standard Coconuts      |  | By-product |
| Poultry Fat                |  | By-product |
| Lard Fat                   |  | By-product |
| Mixed Animals Fat          |  | By-product |

# Feedstocks: Residues

| Feedstock                         | Classification                                                                        |         |
|-----------------------------------|---------------------------------------------------------------------------------------|---------|
| Agricultural residues: Bagasse    |    | Residue |
| Agricultural residues: Cobs       |    | Residue |
| Agricultural residues: Husks      |    | Residue |
| Agricultural residues: Manure     |   | Residue |
| Agricultural residues: Nut shells |  | Residue |
| Agricultural residues: Stalks     |  | Residue |
| Agricultural residues: Stover     |  | Residue |
| Agricultural residues: Straw      |  | Residue |

# Feedstocks: Residues

| Feedstock                                    | Classification                                                                        |         |
|----------------------------------------------|---------------------------------------------------------------------------------------|---------|
| Forestry residues: Bark                      |    | Residue |
| Forestry residues: Branches                  |    | Residue |
| Forestry residues: Cutter shavings           |    | Residue |
| Forestry residues: Leaves                    |   | Residue |
| Forestry residues: Needles                   |  | Residue |
| Forestry residues: Pre- commercial thinnings |  | Residue |
| Forestry residues: Slash                     |  | Residue |
| Forestry residues: Tree tops                 |  | Residue |

# Feedstocks: Residues

| Feedstock                                         | Classification                                                                        |         |
|---------------------------------------------------|---------------------------------------------------------------------------------------|---------|
| Processing residues: Crude glycerine              |    | Residue |
| Processing residues: Crude Tall Oil               |    | Residue |
| Processing residues: Empty palm fruit bunches     |    | Residue |
| Processing residues: Forestry processing residues |   | Residue |
| Processing residues: Palm oil mill effluent       |  | Residue |
| Processing residues: Sewage sludge                |  | Residue |
| Processing residues: Tall oil pitch               |  | Residue |
| Wheat starch slurry                               |  | Residue |

# Non-Biogenic Feedstocks (Carbon + Renewable Power)

- Carbon sources such as industrial **waste gases** or **direct air captured carbon**, combined with **green hydrogen** produced using renewable energy are categorized as non-biogenic feedstocks for SAF production



# Algae as Feedstock

- **Microscopic plants** which can be **grown in wastewater**
- They **absorb CO<sub>2</sub>**, which makes them ideal for **carbon sequestration**
- Produces up to **15 times more oil per square kilometre** than other equivalent feedstock
- Algae are suited to be **grown on marginal lands**, unsuitable for growing food
- Continued **research and development** may result in wider commercial application of this feedstock in the future



# Feedstocks under European Union Renewable Energy Directive (EU RED)

- Under the EU RED II and RED III, SAF feedstocks must meet **strict sustainability and greenhouse gas reduction criteria**
- **Crop feedstocks are not considered eligible** under The EU's ReFuelEU Aviation Regulation. **Only intermediate crops**, if cultivated under certain conditions are found to be eligible
- ReFuelEU focuses on **waste and residue feedstocks** listed in the **EU RED's Annex IX**
- **Part A feedstocks** are those processed with "**advanced technologies**," while **Part B feedstocks** are those processed with "**mature technologies**"
- In addition, the EU focuses on **e-SAF** (commonly also referred to as Renewable fuels of non-biological origin or **RFNBO in EU regulation**) which uses renewable electricity and a variety of carbon sources as feedstocks



# Eligible Feedstocks Under EU RED

## Part A

- **Algae** if cultivated on land in ponds or photobioreactors
- **Biomass fraction** of mixed **municipal waste**
- **Biowaste** from private **households** subject to separate collection
- **Biomass fraction** of **industrial waste** not fit for use in the food or feed chain, including material from retail and wholesale and the agro-food and fish and aquaculture industry
- **Straw**
- **Animal manure** and **sewage sludge**
- **Palm oil mill effluent** and empty **palm fruit bunches**
- **Tall oil pitch**
- **Crude glycerine**
- **Bagasse**



# Eligible Feedstocks Under EU RED

- **Grape marcs and wine lees**
- **Nut shells**
- **Husks**
- **Cobs** cleaned of kernels of corn
- **Biomass fraction of wastes and residues from forestry** and forest-based industries, namely, bark, branches, precommercial thinnings, leaves, needles, tree tops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge,
- **Lignin and tall oil**
- Other **non-food cellulosic material**
- Other **ligno-cellulosic material** except saw logs and veneer logs

## Part B

- **Used cooking oil**
- **Animal fats**



# SAF Production Methods

- SAF conversion processes are evaluated and approved by organizations such as **American Society for Testing and Materials (ASTM) International**
- There are currently **11 ASTM International (ASTM)-approved SAF production pathways** and **11 other** conversion processes are currently **under evaluation**
- **Three of the 11 ASTM-approved SAF production pathways are co-processing pathways**
- ASTM technical standard specification for **sustainable aviation fuel is D7566** and **petroleum-based jet fuel is D1655**



# SAF Approved Production Pathways



| ASTM reference      | Conversion Process                                                                                      | Abbreviation | Possible Feedstocks                            | Maximum Blend Ratio |
|---------------------|---------------------------------------------------------------------------------------------------------|--------------|------------------------------------------------|---------------------|
| ASTM D7566 Annex A1 | Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene                                          | FT           | Coal, natural gas, biomass                     | 50%                 |
| ASTM D7566 Annex A2 | Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids                              | HEFA         | Vegetable oils, animal fats, used cooking oils | 50%                 |
| ASTM D7566 Annex A3 | Synthesized iso-paraffins from hydroprocessed fermented sugars                                          | SIP          | Biomass used for sugar production              | 10%                 |
| ASTM D7566 Annex A4 | Synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources | FT-SKA       | Coal, natural gas, biomass                     | 50%                 |
| ASTM D7566 Annex A5 | Alcohol to jet synthetic paraffinic kerosene                                                            | ATJ-SPK      | Ethanol, isobutanol and isobutene from biomass | 50%                 |
| ASTM D7566 Annex A6 | Catalytic hydrothermolysis jet fuel                                                                     | CHJ          | Vegetable oils, animal fats, used cooking oils | 50%                 |
| ASTM D7566 Annex A7 | Synthesized paraffinic kerosene from hydrocarbon - hydroprocessed esters and fatty acids                | HC-HEFA-SPK  | Algae                                          | 10%                 |
| ASTM D7566 Annex A8 | Synthetic Paraffinic Kerosene with Aromatics                                                            | ATJ-SKA      | C2-C5 alcohols from biomass'                   |                     |

# Hydroprocessed Esters and Fatty Acids (HEFA)



**TRL Level:** 8–9



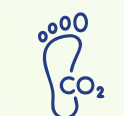
**Feedstocks:** waste and residue fats, vegetable oil, used cooking oil, animal fats, as well as purpose-grown crops like jatropha and camelina



**Process:** feedstocks are processed with hydrogen to remove oxygen and create hydrocarbon fuel components



**Yield (ton distillate/ton feedstock):** 0.83



**Life cycle emissions (gCO<sub>2</sub>e/MJ):** 18.2 for UCO and 64.9 for Soybean oil



**Capital Cost (\$/L total distillate):** 0.4–0.5



**Challenge:** Low availability of sustainable feedstock and competition from other sectors, such as road.

# Gasification and Fischer-Tropsch Process (GFT)



**TRL Level: 8–9**



**Feedstocks:** Agricultural residue, forest residue, municipal solid waste (MSW)



**Process:** The GFT conversion pathway involves both gasification, a thermochemical process (800–1000 degree C) that converts biogenic materials into syngas, followed by Fischer-Tropsch (FT) synthesis that converts the syngas to liquid SAF via catalytic cracking processes



**Yield (ton distillate/ton feedstock):** 0.14 (agri residue), 0.18 (forest residue), 0.31 (MSW)



**Life cycle emissions (gCO<sub>2</sub>e/MJ):** 7.7 (agri residue), 8.3 (forest residue), 32.5 (MSW)



**Capital Cost (\$/L total distillate):** 5.0 (agri residue), 4.0 (forest residue), 2.9 (MSW)



**Challenge:** the gasification of the feedstock remains a challenge as it is typically designed around the specific feedstocks and requires substantial investment, followed by a long construction period and a prolonged period for process stabilization.

# Alcohol to Jet (AtJ)



**TRL Level: 7**



**Feedstocks:** Alcohol (agricultural residues, sugarcane, forest residues, sugar beet, straw, switchgrass, corn grains)



**Process:** The alcohol produced by the biochemical fermentation and thermochemical conversion of lignocellulosic carbohydrates and starch is catalytically upgraded to produce long-chain hydrocarbons. Within the ATJ process technologies, there are three production pathways, namely ethanol-to-jet (ETJ), butanol-to-jet (BTJ), and methanol-to-jet (MTJ). The ETJ and BTJ pathways use bio-based feedstocks like sugarcane, cassava, grain, and corn stover to produce ethanol and butanol for the ATJ process. These feedstocks undergo fermentation or gasification to produce ethanol or butanol. In contrast, MTJ focuses on methanol produced from renewable hydrogen, captured CO<sub>2</sub>, or biomass-derived syn-gas via biomass gasification. These alcohols then go through a series of processes, starting with dehydration, followed by oligomerization, hydrogenation, and fractionalization to produce SAF



**Yield (ton distillate/ton feedstock):** 0.60 (ethanol), 0.75 (iso-butanol)



**Life cycle emissions (gCO<sub>2</sub>e/MJ):** 77.9 (corn), 33.1 (sugarcane)



**Capital Cost (\$/L total distillate):** 0.3



**Challenge:** ATJ needs alcohols made from low-carbon feedstocks and not typical corn, but those streams are scarce and expensive.

# Power-to-Liquid (PtL)



**TRL Level:** 6–7



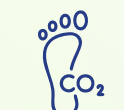
**Feedstocks:** Captured, waste or biogenic CO<sub>2</sub>, renewable electricity, green hydrogen,



**Process:** In the PtL process, green hydrogen, generated from renewable energy, is combined with carbon monoxide, produced from carbon dioxide captured from industrial sites, to create synthetic gas (syngas). This syngas is then converted into SAF using the FT process



**Yield (ton distillate/ton feedstock):** 0.13 – 0.21



**Life cycle emissions (gCO<sub>2</sub>e/MJ):** ~5–20 depending on the electricity source



**Capital Cost (\$/L total distillate):** >4



**Challenge:** As carbon capture technology is still in its early stages of development and green hydrogen manufacturing technology has not yet been commercialized, the overall maturity of this pathway remains low.

# Co-processing Method

- A method where **renewable feedstocks** like vegetable oils or animal fats are **blended with conventional petroleum feedstocks** within an **existing refinery** without major modifications to the refinery infrastructure



# Why Co-processing?

- Fastest way to add SAF to the market
- Existing assets are reused with minor modifications
- CAPEX savings start at 30%
- Well proven technology
- Up to 2 years construction time can be gained
- **Disadvantage:** Maximum blend percentage of SAF produced using co-processing is capped at either 5% or 10% depending on the production pathway



# SAF Approved Co-Processing Pathways



| ASTM reference      | Conversion Process                                                                      | Abbreviation                                        | Possible Feedstocks                                                                   | Maximum Blend Ratio |
|---------------------|-----------------------------------------------------------------------------------------|-----------------------------------------------------|---------------------------------------------------------------------------------------|---------------------|
| ASTM D1655 Annex A1 | Co-hydroprocessing of esters and fatty acids in a conventional petroleum refinery       | FOG                                                 | Vegetable oils, animal fats, used cooking oils from biomass processed with petroleum' | 5%                  |
| ASTM D1655 Annex A1 | Co-hydroprocessing of Fischer-Tropsch hydrocarbons in a conventional petroleum refinery | FT                                                  | Fischer-Tropsch hydrocarbons co-processed with petroleum                              | 5%                  |
| ASTM D1655 Annex A1 | Co-Processing of HEFA                                                                   | Hydroprocessed esters/<br>fatty acids from biomass' |                                                                                       | 10%                 |

# Conversion Processes Under Evaluation

| Conversion Process Under Evaluation                                           | Abbreviation | Lead Developers |
|-------------------------------------------------------------------------------|--------------|-----------------|
| Synthesized Aromatic Kerosene                                                 | SAK          | Virent          |
| Integrated Hydropyrolysis and Hydroconversion                                 | IH2          | Shell           |
| Single Reactor HEFA (Drop-in Liquid Sustainable Aviation and Automotive Fuel) | DILSAAF      | Indian CSIR-IIP |
| Pyrolysis of non-recyclable plastics                                          | ReOIL        | OMV             |
| Co-processing of pyrolysis oil from used tires                                | TPO          | Philips 66      |
| Methanol to jet                                                               | MTJ          | ExxonMobil      |
| Increase in fatty acid/ester co-processing from 5% to 30%                     |              |                 |
| HEFA with higher cycloparaffins'                                              |              | Revo            |
| Biomass pyrolysys                                                             |              | Alder           |
| Biomass/Waste pyrolysis                                                       |              | Green Lizard    |
| Cycloalkanes from Ethanol                                                     |              | Vertimass       |