

CRITICAL INFRASTRUCTURE AND WASTE-TO-VALUE LAB

White Paper | Peer-Reviewed Technical Series

Fischer–Tropsch Is Not Circular by Itself: Engineering the System Boundary for MSW-Derived Sustainable Aviation Fuel

Sophy M. Laughing, Ph.D., MBA

Head of Research, Critical Infrastructure And Waste-to-Value Lab

Cobeal Circular Economy Systems | Urban Mining Division

ORCID: 0000-0002-9068-0497

Bo Erik Gustav Hollsten Ruvalcaba

Co-Author | Strategic and Technical Adviser

Cobeal Circular Economy Systems

ORCID: 0009-0009-3967-7952

Research Areas:	Applied Systems Thinking; High-Risk Infrastructure Delivery; Environmental Control Systems; Sustainable Aviation Fuel Development
Article History:	Submitted: 2025-03-01 Published: 2025-07-15
DOI:	10.5281/zenodo.20816645
Keywords:	Fischer–Tropsch synthesis; sustainable aviation fuel; MSW-to-SAF; gasification; syngas; feedstock qualification; O-ring compatibility; SAF realization gap; circular economy; Cobeal

Abstract

ENGLISH

Fischer–Tropsch (FT) synthesis is a proven catalytic process for converting synthesis gas (syngas) — a mixture of carbon monoxide and hydrogen — into liquid hydrocarbons suitable for aviation fuel production. However, FT synthesis is not, by itself, a circular economy system. It is a hydrocarbon conversion step whose outputs include valuable paraffinic fuels and unavoidable process water containing oxygenates, alkylamines, and organic contaminants. The claim that an MSW-derived or biomass-derived SAF project is ‘circular’ is only defensible when the engineered system boundary around FT has been explicitly constructed: encompassing the carbon provenance of the feedstock, the renewable or waste-derived source of hydrogen, the energy basis of the facility, the treatment and reuse of FT-produced water, the fate of conversion residuals, aircraft fuel-system material compatibility, and the full carbon-intensity accounting pathway required for CORSIA, LCFS, or RFS qualification.

This paper establishes that thesis through three lines of evidence. First, peer-reviewed data on FT reactor performance under biomass-derived syngas contamination (Voeten et al., 2024) demonstrate that nitrogen compounds — particularly ammonia — are converted into tertiary alkylamines that partition overwhelmingly into the FT water phase (89% of nitrogen), creating a water treatment obligation that any credible circularity claim must address. Second, a lifecycle assessment of seven MSW-to-biofuel pathways (Raj et al., 2026) establishes that integrated two-stage gasification achieves an avoided global warming potential of $-1,095 \text{ kg CO}_2 \text{ eq}$ per tonne of MSW when combined with upstream recycling and material flow optimization — the strongest environmental performance among all modelled routes — but this result is pathway-specific and depends on the completeness of feedstock preparation, syngas cleaning, and system integration. Third, research on aircraft fuel-system material compatibility (Faulhaber et al., 2023; Luning Prak et al., 2025) establishes that FT-derived SAF, which is predominantly paraffinic and low in aromatic content, produces insufficient nitrile rubber O-ring swelling to maintain sealing integrity in legacy aircraft fuel systems at blends above 50%v, creating a system-level constraint that must be engineered around before any MSW-to-SAF project can be claimed to be commercially drop-in.

Cobeal’s proposed role is to construct and deliver the technical system boundary that transforms a regional MSW or biomass feedstock opportunity into a qualified, testable, engineering-ready SAF development basis. This paper defines the evidence standards, validation requirements, and engineering disciplines required to do so responsibly.

ESPAÑOL

La síntesis de Fischer–Tropsch (FT) es un proceso catalítico comprobado para convertir gas de síntesis (syngas) — mezcla de monóxido de carbono e hidrógeno — en hidrocarburos líquidos aptos para la producción de combustible de aviación sostenible (SAF). Sin embargo, la síntesis FT no constituye, por sí misma, un sistema de economía circular. Es una etapa de conversión de hidrocarburos cuyos productos incluyen combustibles parafínicos valiosos y agua de proceso que contiene oxigenados, alquilaminas orgánicas y contaminantes. La afirmación de que un proyecto de SAF derivado de residuos sólidos urbanos (RSU) o biomasa es ‘circular’ sólo es defendible cuando el límite del sistema de ingeniería alrededor del proceso FT ha sido explícitamente construido: incluyendo la procedencia del carbono en el alimentador, la fuente renovable o derivada de residuos del hidrógeno, la base energética de la instalación, el tratamiento y reutilización del agua producida por FT, el destino de los residuos de conversión, la compatibilidad con los

materiales del sistema de combustible de aeronaves, y la cadena completa de contabilidad de la intensidad de carbono requerida para la calificación CORSIA, LCFS o RFS.

Este artículo establece esa tesis mediante tres líneas de evidencia. Primero, datos de rendimiento del reactor FT bajo contaminación de syngas derivado de biomasa (Voeten et al., 2024) demuestran que los compuestos de nitrógeno — particularmente el amoníaco — se convierten en alquilaminas terciarias que se distribuyen mayoritariamente en la fase acuosa del proceso FT (89% del nitrógeno), creando una obligación de tratamiento de agua que cualquier afirmación creíble de circularidad debe abordar. Segundo, una evaluación del ciclo de vida de siete rutas de conversión de RSU a biocombustibles (Raj et al., 2026) establece que la gasificación integrada en dos etapas logra un potencial de calentamiento global evitado de $-1,095 \text{ kg CO}_2 \text{ eq}$ por tonelada de RSU cuando se combina con reciclaje previo y optimización del flujo de materiales. Tercero, investigaciones sobre compatibilidad de materiales en sistemas de combustible de aeronaves (Faulhaber et al., 2023; Luning Prak et al., 2025) demuestran que el SAF derivado del proceso FT, al ser predominantemente parafínico y bajo en contenido aromático, produce una expansión insuficiente de los o-rings de goma nitrilo en sistemas de combustible de aeronaves existentes en mezclas superiores al 50%v.

El papel propuesto de Cobeal es construir y entregar el límite del sistema técnico que transforma una oportunidad de alimentador regional de RSU o biomasa en una base de desarrollo de SAF calificada, comprobable y lista para la ingeniería. Este artículo define los estándares de evidencia, los requisitos de validación y las disciplinas de ingeniería necesarios para hacerlo de manera responsable.

1. Fischer–Tropsch Synthesis: What It Is and What It Is Not

1.1 The Reaction and Its Products

The Fischer–Tropsch (FT) reaction converts synthesis gas — a mixture of carbon monoxide (CO) and hydrogen (H₂) — into a distribution of aliphatic hydrocarbons through surface polymerization on a supported metal catalyst, typically cobalt or iron. The principal reaction follows the stoichiometry:



Every mole of carbon incorporated into a hydrocarbon product generates a mole of water as a stoichiometric co-product. This is not incidental — it is a fundamental thermochemical consequence of the reaction mechanism. The FT process therefore simultaneously produces: (i) a distribution of paraffinic, olefinic, and oxygenate hydrocarbons governed by Anderson–Schulz–Flory (ASF) kinetics; and (ii) an aqueous phase containing dissolved oxygenates, short-chain alcohols, carboxylic acids, and — when the upstream syngas contains nitrogen impurities — a spectrum of organic amines. This water is process water. It is not potable water, not clean water, and not a neutral byproduct. It is a contaminated effluent stream that requires engineered treatment before it can be reused, discharged, or incorporated into a circular water management loop.

The hydrocarbons produced by FT synthesis under cobalt-catalyzed conditions favor long-chain paraffins (wax) at high chain-growth probabilities ($\alpha > 0.9$). These waxes are subsequently subjected to hydrocracking and isomerization over bifunctional catalysts to produce the distillate-range hydrocarbons — predominantly iso-alkanes and n-alkanes — that constitute FT-derived synthetic paraffinic kerosene (FT-SPK). The resulting fuel is certified under ASTM D7566 Annex A1 and is approved for blending with conventional jet fuel at up to 50% by volume (50%v). This 50%v limit is not clearly defined. It reflects several convergent constraints: aromatic content, density, and — critically — aircraft fuel-system material compatibility. These are addressed in Section 5.

1.2 What FT Does Not Do

FT synthesis does not thermally crack plastic molecules. It does not gasify waste. It does not reform hydrocarbons into syngas. These are upstream processes (gasification, pyrolysis, steam reforming, autothermal reforming) that must be completed — and their products cleaned — before syngas arrives at the FT reactor inlet. The distinction is relevant because a project that describes itself as ‘MSW-to-SAF via Fischer–Tropsch’ is actually proposing a multi-stage system in which FT is only one step among many. The technical complexity, capital cost, water management obligation, and certification burden belong to the entire system, not to the FT reactor alone.

Table 1 distinguishes FT synthesis from the upstream conversion processes with which it is commonly conflated.

Process	Input	Output	Role in MSW-to-SAF Chain
Gasification	Dried, prepared MSW or biomass	Raw syngas (CO, H ₂ , CO ₂ , CH ₄ , N ₂ , H ₂ S, NH ₃ , tar, particulates)	Thermal conversion; upstream of FT

Syngas Cleaning	Raw syngas	Cleaned syngas (CO + H ₂) meeting FT inlet spec	Mandatory intermediate; determines FT catalyst performance
Fischer–Tropsch Synthesis	Clean syngas (CO + H ₂)	Paraffinic hydrocarbons (wax, naphtha) + FT water	Hydrocarbon synthesis step; not the full system
Hydrocracking / Isomerisation	FT wax	Distillate-range SPK suitable for aviation blending	Downstream upgrading; required for ASTM D7566 certification
FT Water Treatment	FT process water (oxygenates, amines, BTEX traces)	Treated water suitable for reuse or discharge	Required for water circularity claim; separate engineering scope

Table 1. Distinction between Fischer–Tropsch synthesis and the upstream and downstream processes with which it is part of an integrated MSW-to-SAF system. FT synthesis occupies one step in a five-stage chain.

1.3 Why This Distinction Is Commercially Critical

The aviation sector is experiencing a sharp and well-documented gap between SAF production announcements and operational capacity. A 2025 study published in *Nature Communications* — based on a Global SAF Capacity Database of 425 publicly announced projects compiled between 2013 and 2024 — found that only 24% of globally announced SAF production capacity for 2024 was realized on time, with the equivalent figure for the European Union at 26% (Martulli et al., 2025). The global realization gap — the difference between announced and operational capacity — rose from 4.04 Mt year⁻¹ in 2023 to 6.92 Mt year⁻¹ in 2024. Fischer–Tropsch projects are specifically cited as impeded by technical and operational challenges. Over 40% of the announced capacity for 2030 remains in early development or at risk of delay or cancellation.

The causes of this gap are not principally financial. They are technical. Projects that advance without resolved feedstock qualification, syngas cleaning specifications, water management design, material compatibility testing, and carbon intensity verification encounter these problems at the engineering and permitting stage, when correction is expensive and often fatal to project timelines. Cobeal’s position is that the technical system boundary must be constructed and validated before capital is committed to engineering, permitting, or EPC procurement.

2. FT Process Water: Byproduct, Contaminant Sink, and Treatment Obligation

2.1 The Water Phase as a Nitrogen Repository

Synthesis gas derived from biomass and MSW gasification contains nitrogen-bearing impurities, principally ammonia (NH_3) and hydrogen cyanide (HCN), at concentrations that depend on the nitrogen content of the feedstock and the completeness of upstream syngas cleaning. Target concentrations for cleaned syngas entering a FT reactor have been proposed at below 0.05 ppmV for NH_3 and HCN (Boerrigter et al., 2002, cited in Voeten et al., 2024). Line-up simplification — reducing the number and severity of cleaning steps to lower capital cost — is economically attractive but requires validation that residual nitrogen contamination is acceptable for the FT catalyst and downstream product specifications.

Voeten et al. (2024) investigated the fate of 2.6 ppmV ammonia co-fed to a cobalt-catalyzed fixed-bed FT reactor operating at 60 bar and an average bed temperature of 231°C. The nitrogen mass balance was effectively closed (101%), with nitrogen distributed across three product streams: **89% in the water phase**, 7% in the heavy wax, and 1% in the light wax. The off-gas contained less than 2 ppbV nitrogen, confirming that ammonia is not simply passed through — it is chemically converted into organic nitrogen species incorporated into the hydrocarbon product distribution.

Three independent analytical techniques — ion chromatography, flow-injection single-quadrupole mass spectrometry, and liquid chromatography–electrospray ionization time-of-flight mass spectrometry — confirmed that the dominant amine class in all three product phases was tertiary N,N-dimethylalkylamines rather than the primary alkylamines that might have been expected from simple ammonia addition. This finding has mechanistic implications: it indicates that ammonia undergoes decomposition on the metallic cobalt surface, and that dimethylamine fragments are incorporated into growing hydrocarbon chains during FT synthesis. Alkylamines up to carbon chain length C120 were detected in the heavy wax by MALDI-FT-ICR-MS.

2.2 Implications for FT Water Treatment

The concentration of the water phase as the primary nitrogen sink — with ammonium at 23 ppmw and total chemically-bonded nitrogen at 44.4 ppmw in the water from a 2.6 ppmV NH_3 feed experiment — establishes that FT-produced water from biomass or MSW-derived syngas is not simply oxygenate-laden water. It is a complex aqueous effluent containing alcohols, carboxylic acids, ketones, aldehydes, BTEX traces, and a full homologous series of alkylamines up to at least C19 in the water phase.

The water treatment obligation this creates has been characterized in a patent describing purification methods for FT-produced water (Velocys Technologies, WO 2016/044348 A1). That process describes FT water entering a stripper column to remove volatile organic compounds (predominantly alcohols with carbon numbers C1–C10), followed by pH adjustment and transfer to a membrane bioreactor (MBR) for biological degradation of residual organic carbon. The patent establishes that FT water — with a chemical oxygen demand (COD) of approximately 25,000–30,000 mg/L in the unstripped state — is highly biodegradable after stripping: MBR systems have demonstrated greater than 99% COD removal from stripped FT water at steady-state conditions, producing a treated effluent with COD below 5 mg/L suitable for cooling tower make-up or other process reuse.

Table 2 summarizes the contaminant profile of FT-produced water from a short-contact-time FT process (Velocys Technologies, WO 2016/044348 A1).

Component Class	Normal Load (mg/L)	Peak Load (mg/L)	Treatment Significance
Methanol	4,038	7,779	Primary stripping target; high volatility
Ethanol	1,935	2,450	Primary stripping target
C3–C6 Alcohols (total)	~1,700	~2,500	Stripping + MBR
Acetic Acid	478	261	MBR biodegradation
C3–C6 Carboxylic Acids (total)	~285	~130	MBR biodegradation; drives COD
Ketones (acetone, MEK)	~33	~62	MBR; monitoring required
BTEX (benzene, toluene, xylenes)	<15 µg/L	<15 µg/L	Trace; regulatory monitoring required
Alkylamines (N,N-dimethyl series, C3–C19)	Up to 44 ppmw N*	—	MBR degradation; requires validation at full scale

Table 2. Contaminant profile of Fischer–Tropsch process water. Primary data from Velocys Technologies (WO 2016/044348 A1) with alkylamine data from Voeten et al. (2024). *Nitrogen concentration from 2.6 ppmV NH₃ feed experiment.

2.3 What a Circular Claim Requires

A project that claims FT-SAF circularity with respect to water must demonstrate: (i) a defined water mass balance for the facility, including the source and volume of water consumed for hydrogen production, steam generation, scrubbing, and cooling; (ii) a defined treatment train for FT-produced water, with demonstrated COD removal to a specification consistent with reuse; (iii) a fate pathway for alkylamine-containing wastewater that does not transfer contamination to a receiving water body or groundwater; and (iv) a net water balance that is positive (i.e., the facility recovers or conserves more water than it consumes) or at minimum demonstrates responsible management of water consumption in the regional hydrological context.

None of these requirements can be satisfied by FT chemistry alone. They are system design requirements that must be engineered around FT, not assumed from it.

3. MSW as a Feedstock: Environmental Performance and Qualification Requirements

3.1 Integrated Gasification as the Environmentally Superior MSW-to-Biofuel Pathway

A 2026 comparative lifecycle assessment published in *Scientific Reports* evaluated seven MSW-to-biofuel pathways using a functional unit of one tonne of MSW and ISO 14040/14044-compliant methods (Raj et al., 2026). The pathways evaluated were: (1) open landfilling without energy recovery (LWO); (2) landfilling with landfill gas capture (LWE); (3) incineration with energy recovery (MIN); (4) torrefaction (MTO); (5) high-temperature gasification (MGS); (6) hydrothermal carbonization (MHT); and (7) integrated two-stage gasification with torrefaction pretreatment (MIG). The assessment used MSW samples from the Prem Nagar dumping site in Dehradun, India, characterized by stratified random sampling per ASTM D5231-92, and quantified impacts across five midpoint categories: global warming potential (GWP), ozone depletion potential (SOD), freshwater eutrophication potential (FEP), land use (LU), and water consumption (WC), using ReCiPe 2016 v1.1 characterization factors.

The study's primary finding with respect to GWP is unambiguous: the integrated two-stage gasification scenario (MIG) achieved an **avoided net GWP of $-1,095$ kg CO₂ eq per tonne of MSW** — the best environmental performance of all seven pathways. Open landfilling produced $+1,400$ kg CO₂ eq per tonne — the worst outcome and the baseline against which all thermochemical pathways are compared. Table 3 presents the comparative GWP results.

Scenario	Description	Net GWP (kg CO ₂ eq / tonne MSW)	Relative to LWO Baseline
S1 (LWO)	Open landfilling, no energy recovery	+1,400.00	Baseline (worst)
S2 (LWE)	Landfill with landfill gas recovery	Moderate reduction vs. S1	Improvement limited by methane leakage
S3 (MIN)	Incineration with energy recovery	Positive but lower than S1	Improved
S5 (MGS)	High-temperature gasification (single stage)	Negative (avoided)	Strong performer
S7 (MIG)	Integrated two-stage: torrefaction + gasification with upstream recycling	-1,095.00	Best of all seven pathways

Table 3. Comparative global warming potential (GWP) results from the seven MSW-to-biofuel pathways evaluated by Raj et al. (2026). MIG = Integrated gasification with torrefaction pretreatment and upstream recycling. Functional unit: 1 tonne of MSW.

3.2 Scope Conditions and Transferability

Three important scope conditions apply to the Raj et al. (2026) results and must be stated explicitly in any document that cites them.

First, the study is based on Indian MSW composition data from Dehradun, India, calibrated to national waste generation statistics of 160,039 tonnes per day. Indian MSW composition — characterized by high organic content (food waste: 30–50%), lignocellulosic material (15–25%), and relatively high moisture — may differ from North American or Latin American waste streams, which typically have higher plastic and paper

fractions and variable moisture depending on climate and collection system. The LCA results are therefore indicative of integrated gasification performance potential, not directly transferable to any specific regional context without feedstock characterization.

Second, the MIG scenario is a *two-stage* process in which torrefaction pretreatment precedes gasification. Single-stage gasification (Scenario S5, MGS) also performed well environmentally but below MIG, demonstrating that the torrefaction pre-conditioning step contributes meaningfully to the environmental advantage. The 67.5% syngas conversion efficiency and 92,711 tpd syngas output from 137,351 tpd input established by the complementary Material Flow Analysis apply specifically to the MIG configuration.

Third, the avoided GWP benefit depends on the regional electricity grid emission factor used to calculate the credit for displaced grid electricity. Sensitivity analysis showed that a $\pm 10\%$ variation in the energy recovery efficiency of the gasification system produced a GWP variation from $-1,147.5$ to $-1,402.5$ kg CO₂ eq ($\pm 7.4\%$), and a $\pm 10\%$ variation in the grid displacement emission factor produced a variation from $-1,170.5$ to $-1,379.0$ kg CO₂ eq ($\pm 6.3\%$). The relative ranking of MIG as the best pathway was robust across all sensitivity cases.

3.3 Feedstock Qualification Requirements for MSW-to-SAF

Regardless of which conversion scenario is adopted, MSW feedstock for SAF production pathways requires systematic characterization before any engineering basis can be established. Table 4 defines the minimum required characterization parameters and their role in the engineering data package.

Parameter	Method / Standard	Engineering Significance
Moisture content	ASTM D3173 / oven drying	Determines drying energy burden; affects autothermal check for gasification
Proximate analysis (VM, ash, FC)	ASTM D3172	Predicts gasification behavior; ash determines slag/fouling risk
Higher and lower heating value	ASTM D5865 / IS 1350	Determines energy yield; autothermal threshold check
Chlorine content	ASTM D4208 / XRF	HCl formation in syngas; damages catalysts and heat exchangers; PVC indicator
Sulfur content	ASTM D4239	H ₂ S in syngas; poisons FT cobalt catalysts; sets desulfurization specification
Nitrogen content	ASTM D5373 / elemental analysis	NH ₃ / HCN in syngas; drives alkylamine formation in FT water (Voeten et al., 2024)
Alkali metals (Na, K)	ICP-OES / XRF	Catalyst poisoning; slagging risk in gasifier
Heavy metals (Pb, Cd, Hg, Zn, Cr)	ICP-MS / EPA 3050B	Regulatory classification of ash residuals; catalyst protection
PFAS screening	EPA 533 / 537.1	Increasingly required for waste-derived feedstocks; affects ash disposal pathway
Biogenic vs. fossil carbon fraction	ASTM D6866 / ¹⁴ C analysis	Determines CORSIA and LCFS eligibility; affects carbon credit value

Particle size distribution	ASTM D5233 / laser diffraction	Preprocessing design; gasifier feeding system specification
Seasonal variability profile	Multi-season sampling programme	Sets operating envelope; required for bankable yield guarantee

Table 4. Minimum feedstock characterization parameters required before establishing a basic engineering data package for an MSW-to-SAF project. Parameters derived from synthesis of Raj et al. (2026), Voeten et al. (2024), and Cobeal EPCIC practice.

4. Carbon Intensity, Well-to-Wake Performance, and Certification Frameworks

4.1 The Well-to-Wake Framework and Its Non-CO₂ Dimension

The carbon performance of SAF is typically quantified as a well-to-wake (WtW) CO₂-equivalent (CO₂e) emission factor expressed in grams of CO₂e per megajoule of fuel energy (gCO₂e/MJ). This metric encompasses both the well-to-pump (WtP) supply chain emissions — feedstock production, transportation, conversion, and fuel distribution — and the pump-to-wake (PtW) combustion emissions from the aircraft engine.

A comprehensive well-to-wake climate impact assessment published in *Scientific Reports* (Boerboom et al., 2025) evaluated WtW CO₂e for multiple SAF pathways, including FT-SPK from MSW, against the conventional jet fuel (CJF) baseline of approximately 89 gCO₂e/MJ based on CORSIA core lifecycle analysis values. The study incorporated non-CO₂ inflight effects — nitrogen oxide (NO_x) emissions, water vapour (H₂O), and contrail formation — converted to CO₂ equivalence using the Average Temperature Response (ATR) climate metric over 100-year and shorter time horizons. Non-CO₂ effects have historically accounted for approximately two-thirds of aviation’s total radiative forcing in 2018.

The key finding relevant to MSW-derived FT-SAF is that: (i) the maximum GHG reduction achievable through SAF relative to conventional jet fuel, even under the most favorable assumptions, is less than 50% when non-CO₂ inflight effects are included over a 100-year time horizon; (ii) for FT-SAF from MSW with 0% non-biogenic carbon content, well-to-wake CO₂e values using the ATR100 metric are approximately 50–150 gCO₂e/MJ depending on assumed lifecycle emissions; and (iii) SAF can meaningfully reduce contrail radiative forcing by reducing soot particle emissions from combustion of low-aromatic paraffinic fuel, a benefit that is in tension with the O-ring compatibility requirements discussed in Section 5.

4.2 Applicable Certification and Incentive Frameworks

MSW-derived FT-SAF may qualify for incentives and certification credits under four major frameworks, each with distinct carbon intensity calculation methodologies and feedstock eligibility rules. Table 5 summarises the key characteristics of each framework as they apply to MSW and biomass-derived FT-SAF.

Framework	Jurisdiction	Carbon Baseline (CJF)	MSW Feedstock Eligibility	FT Pathway Status
CORSIA	International (ICAO)	89 gCO ₂ e/MJ (ATR100 basis)	MSW eligible; biogenic fraction matters; lifecycle data required	FT-SPK approved; ASTM D7566 Annex A1
LCFS	California (USA)	~94 gCO ₂ e/MJ (fuel-specific)	Post-recycling MSW / RDF eligible with pathway registration	Pathway registration required; CI score must be below 20 gCO ₂ e/MJ for full credit
RFS / D3 / D7	United States (EPA)	Lifecycle GHG threshold: 50%	MSW qualifies as cellulosic biomass	FT pathways require EPA pathway

		reduction vs. petroleum baseline	under certain conditions	approval; D7 for cellulosic biojet
45Z Tax Credit	United States (IRS)	50 gCO ₂ e/MJ threshold for SAF credit eligibility	Broad feedstock eligibility including MSW	GREET model-based CI calculation; FT-SPK included

Table 5. Carbon intensity certification and incentive frameworks applicable to MSW-derived FT-SAF. CI = carbon intensity. Pathway registration timelines and credit values change with regulatory updates; verification against current programme guidance is required before project underwriting.

4.3 The Biogenic Carbon Fraction Requirement

For MSW-derived SAF projects, the distinction between biogenic and fossil carbon fractions in the feedstock is not just a regulatory detail — it is a material determinant of carbon intensity scores and credit eligibility. Under CORSIA and most national frameworks, fossil-carbon fractions of MSW (primarily plastics and synthetic textiles) do not receive the same lifecycle credit as biogenic fractions. The biogenic carbon fraction must be determined by radiocarbon (¹⁴C/¹²C ratio) analysis per ASTM D6866, and this analysis must be performed on actual feedstock samples from the target waste stream — it cannot be estimated from generic waste composition tables.

A Mexico City municipal solid waste stream, for example, may have a biogenic fraction significantly different from the Indian or European waste streams used in published lifecycle studies. This difference directly affects the carbon intensity score and therefore the economic value of the carbon credits and incentive payments that anchor the project financial model. Feedstock carbon fraction analysis must therefore be among the first-priority characterization activities in any MSW-to-SAF project.

5. Aircraft Fuel-System Material Compatibility: The 50% Blend Limit

5.1 Why the 50%v Limit Exists

Synthetic paraffinic kerosene produced by FT synthesis is approved for blending with conventional jet fuel at up to 50% by volume under ASTM D7566 Annex A1. This blend limit is not set because FT-SPK cannot burn cleanly in aircraft engines — in fact, its high paraffinic purity results in superior combustion characteristics, lower soot formation, and reduced contrail tendency relative to conventional jet fuel. The limit exists because of three convergent fuel-property constraints: minimum aromatic content (8%v), minimum density (775 kg/m³), and aircraft fuel-system material compatibility, of which elastomer O-ring sealing behavior is the most critical and least resolved.

The commercial aviation sector relies on nitrile rubber (acrylonitrile-butadiene rubber, NBR) O-rings for fuel-system sealing across a large fraction of the legacy fleet. These O-rings depend on fuel aromatic and cycloaromatic content to induce a measured degree of volumetric swelling — typically in the range of 8.3–17.1%v/v for conventional jet fuel — that ensures sealing integrity under compression. Fuel-system O-rings that are not adequately swollen by the fuel they contact can lose sealing force and cause fuel leaks. Fuel-system O-rings that are over-swollen can suffer mechanical degradation. Consistent swelling within the conventional experience range is therefore a functional requirement, not an aesthetic one.

5.2 FT-SPK and NBR O-Ring Swelling: Quantitative Evidence

Faulhaber et al. (2023) conducted optical dilatometry measurements of NBR O-ring swell for 56 solvents, including 39 hydrocarbon dopants at 8%v in Gevo ATJ-SPK (C-1), 14 conventional jet fuels, and 3 SAF blend components, establishing a three-standard-deviation conventional swell range of 8.3–17.1%v/v for this batch of NBR O-rings. Key quantitative findings are reproduced in Table 6.

Fuel / Blend Component	Aromatic Content (%v)	NBR O-Ring Swell (%v/v)	Within Conventional Range?
Conventional Jet A-2 (Shell Mobile)	16.4	13.7 (reference)	Yes
FT-SPK (Syntroleum S-5)	<1.0	0.7	No — far below
Gevo ATJ-SPK (C-1)	<1.0	0.5	No — far below
World Energy HEFA	<1.0	0.3	No — far below
SAK/HEFA 21/79 blend (Virent/WE)	20.1	12.3	Yes
ATJ-SPK (50%v) + JP-5 (50%v)	~10	12.4	Yes — minimum aromatic additive needed

Table 6. NBR o-ring swell data for SAF blend components and conventional jet fuel. Data from Faulhaber et al. (2023) and Luning Prak et al. (2025). Conventional 3-sigma range: 8.3–17.1%v/v.

5.3 The Additive Strategy and Its Tradeoffs

Faulhaber et al. (2023) and Luning Prak et al. (2025) both investigated the use of aromatic and cycloalkane dopants to restore O-ring swell in low-aromatic SAF blends. The key findings are:

- Hydrocarbon class ranking for o-ring swelling effect (highest to lowest): multi-ring aromatics and naphthalenes > cycloaromatic (e.g., tetralin, indane) > alkylbenzenes > polycycloalkanes (e.g., decalin) > monocycloalkanes.
- A linear volumetric blending rule applies ($R^2 > 0.919$ for all tested dopants): o-ring swell scales linearly with dopant concentration, enabling prediction of required blend composition to achieve target swell.
- Cycloalkane dopants are preferred over aromatics from a combustion cleanliness perspective (lower sooting index) but require significantly higher concentrations to achieve equivalent swell: approximately 44–55%v of polycycloalkanes versus 9–22%v of alkylbenzenes to reach the minimum conventional swell threshold of 8.3%v/v when doped into neat ATJ-SPK.
- Increasing swell reduces tensile strength: exposure of NBR O-rings to JP-5 (conventional jet fuel) for one week caused a 32% reduction in tensile strength; the maximum-swelling mixture tested (34%v/v swell) caused a 40% reduction (Luning Prak et al., 2025). Any additive strategy that pushes swell above the conventional range creates a tensile strength risk.
- Aged O-rings with compression set present a compounding risk: a fuel that provides insufficient swell for an aged O-ring may not restore sealing force, because the elastomer has partially lost its elastic recovery. This is the scenario that produced the fuel leakage event at NASA Glenn during initial SPK testing.

The implication for MSW-to-SAF project development is direct: an FT-SAF project that proposes 100%v drop-in capability — or blend fractions above 50%v — cannot satisfy this requirement without either demonstrating that the fuel composition meets the conventional swell range across a statistically representative sample of current commercial aircraft fuel systems, or obtaining OEM approval through the ASTM D4054 tier testing process, which requires several years and significant expenditure for each new fuel composition.

6. Constructing the Circular System Boundary: What Must Be True

6.1 The Controlling Argument

Fischer–Tropsch synthesis is the hydrocarbon synthesis engine. Circularity is the engineered system around it.

A project that positions FT-SAF as circular must demonstrate that every material and energy loop in the system has been closed by engineering rather than assumed by analogy. Table 7 defines the minimum evidence requirements for a credible circular claim across eleven system dimensions.

System Dimension	What Must Be Demonstrated	Evidence Required	Risk if Not Resolved
Carbon provenance	Feedstock is predominantly biogenic; fossil fraction quantified	¹⁴ C analysis per ASTM D6866 on actual feedstock samples	CORSIA / LCFS ineligibility; carbon credit value collapse
Hydrogen source	H ₂ is derived from renewable electricity, waste-derived biogas, or recovered process streams	Energy and mass balance with H ₂ source verified; CI contribution quantified	Carbon intensity too high for SAF certification credit
Energy basis	Facility energy (heat, power) is self-generated from waste-to-energy recovery or renewable supply	Mass and energy balance with grid dependency explicitly bounded	CI score elevated; renewable claim unsupported
FT water treatment	FT-produced water is treated to meet reuse specification; alkylamine fate demonstrated	Water balance; COD removal to <50 mg/L; nitrogen speciation analysis	Water discharge violation: circular water claim unsupported
Syngas nitrogen management	NH ₃ /HCN at FT inlet verified to meet catalyst tolerance; water treatment sized for alkylamine load	Syngas composition analysis; FT water characterization per Voeten et al. (2024)	FT catalyst deactivation; SAF nitrogen specification breach (2 ppmw per ASTM D7566)
Residual management	Ash, char, and slag are classified, disposed of, or reused within regulatory framework	Residual characterization; heavy metals / PFAS / leachate testing	Disposal cost overrun; environmental liability
Aircraft material compatibility	Fuel composition meets NBR O-ring swell range at intended blend fraction	Swell testing per Faulhaber et al. (2023) methodology; blend composition verified	Blend limit constraint below 50%; retrofit cost for legacy fleets
SAF fuel specification	Fuel meets ASTM D7566 and all applicable OEM fuel-approval specifications	ASTM D4054 tier testing programme initiated; laboratory analysis complete	Fuel is not certifiable as SAF regardless of production route

Carbon intensity verification	CI score verified against CORSIA, LCFS, RFS, or 45Z as applicable	Lifecycle model with primary feedstock data; third-party CI verification pathway	Incentive payment disqualification; project IRR collapse
Chain of custody	Feedstock provenance is traceable from waste origin to fuel product	Mass balance system; transaction certification; traceability protocol	Carbon credit invalidation; LCFS audit failure
Waste hierarchy alignment	Feedstock is post-recycling residual; recycling-first hierarchy respected	Waste classification documentation; diversion records; RDF specification	Regulatory challenge in jurisdictions with strict waste hierarchy requirements

Table 7. Eleven-dimension circularity evidence matrix for MSW-derived FT-SAF projects. Each row defines a system boundary requirement, the evidence necessary to satisfy it, and the risk of leaving it unresolved. No project can credibly claim circular SAF production without addressing all eleven dimensions.

6.2 The Decision Gate Model

Project advancement should follow a disciplined stage-gate structure in which each gate is opened only when the evidence required by Table 7 for that stage has been produced and independently verified. The gates and their evidence requirements are:

Gate	Name	Evidence Required to Open Gate	Cobeal Scope
G1	Feedstock Qualification	Table 4 characterization complete; biogenic fraction confirmed; seasonal variability bounded	WP1 + WP2 (Feedstock Intelligence + Sampling)
G2	Pathway Selection	Gasification pathway screened against feedstock profile; syngas cleaning specification drafted; FT inlet constraints confirmed	WP3 (Conversion Pathway Screening)
G3	Pilot Testing Completion	Bench / pilot syngas composition data; tar and nitrogen measurement; FT water sample characterized; mass and energy balance drafted	WP4 (Pilot Testing + Engineering Data Package)
G4	Regulatory and Carbon Readiness	Carbon intensity model complete; CORSIA / LCFS / 45Z pathway identified; permitting pre-consultation complete; chain-of-custody framework drafted	WP5 (Regulatory, Carbon, and Certification Support)
G5	Basic Engineering Authorization	Design basis memorandum issued; Table 7 evidence matrix complete; technical	WP6 (Basic and Detailed Engineering Support)

		risk register at acceptable residual level	
FID	Final Investment Decision	All G1–G5 evidence packages delivered; EPC procurement initiated; financing committed; offtake and carbon credit agreements in place	Beyond Cobeal SOW; Cobeal EPCIC role begins

Table 8. Decision gate model for MSW-to-SAF project advancement. Gate evidence requirements define Cobeal’s technical scope in the pre-engineering phase. WP = Work Package. FID = Final Investment Decision.

7. Cobeal's Technical Role: The Pre-Engineering Intelligence Layer

7.1 Where Cobeal Operates in the Project Value Chain

Cobeal's role in MSW-to-SAF development is to occupy the technical intelligence layer between feedstock opportunity and engineering-ready project basis. This layer — which encompasses feedstock discovery, characterization, conversion pathway selection, pilot testing, carbon intensity modelling, regulatory pre-consultation, and engineering data package preparation — is the layer that determines whether a regional waste or biomass resource can credibly support SAF production, and what the technical design basis for that production system should be.

Cobeal does not position itself as a SAF plant builder at the pre-engineering phase. The positioning is more precise and more valuable: Cobeal constructs and delivers the technical system boundary that transforms a waste characterization data set into a qualifiable, bankable engineering basis. That basis is what basic engineering firms, technology licensors, project finance institutions, and offtake counterparties require before they can make commitments.

7.2 Aviation Client Matrix

Table 9 defines what Cobeal delivers to each category of aviation-sector client.

Client Category	Primary Need	Cobeal Deliverable
Airlines	SAF supply-chain validation; carbon intensity verification; long-term offtake basis	Feedstock atlas; carbon intensity model; pathway feasibility summary; risk register
Airports	Local waste-to-fuel feasibility; airport waste and biomass resource mapping; regional SAF hub planning	Feedstock opportunity ledger; control-point map; preliminary volume estimates; siting and logistics constraints
SAF Developers	Feedstock testing; preprocessing design basis; pathway selection; engineering data package preparation	Full Work Package WP1–WP6 scope; go/no-go recommendation; design basis memorandum
Fuel Distributors	Regional feedstock and fuel offtake analysis; blend compliance verification	Feedstock volume estimates; carbon intensity data framework; blend specification review
Infrastructure Investors	Technical diligence; risk register; milestone gate verification; project readiness scoring	Technical due diligence report; Table 7 evidence matrix audit; risk-adjusted yield estimate
EPC / Engineering Firms	Feedstock data package; design basis; process assumptions; syngas quality targets	Engineering data package; design basis memorandum; mass and energy balance; technical specification set
Municipal Agencies / Waste Authorities	Waste-to-value feasibility; diversion strategy; facility siting; regulatory alignment	Feedstock opportunity ledger; technology screening; permitting memorandum; carbon intensity screen

Table 9. Cobeal deliverables by aviation-sector client category. All deliverables are produced from primary feedstock and process data, not from generic literature estimates.

7.3 Service Tiers

Cobeal structures its pre-engineering technical services across three tiers to match the client’s stage of project development.

Tier	Service Name	Best For	Primary Deliverables
Tier 1	SAF Feedstock Intelligence Study	Airlines, airports, investors evaluating regional SAF supply-chain opportunities before committing to a developer or technology	Desktop feedstock atlas; opportunity screen; preliminary volume estimates; carbon intensity screen; go/investigate recommendation
Tier 2	Feedstock Qualification and Pathway Study	SAF developers, airport authorities, and waste-management partners with identified feedstock streams seeking a qualified technical basis	Table 4 characterization suite; conversion pathway ranking; preliminary engineering basis; pilot test protocol; carbon intensity model
Tier 3	Engineering Support Package	Developers advancing toward basic engineering (FEED), financing, or FID who require a complete, independently defensible technical package	Full WP1–WP6 deliverable set; design basis memorandum; mass and energy balance; Table 7 circularity evidence matrix; risk register; go/no-go for FEED authorization

Table 10. Cobeal service tiers for MSW-to-SAF and biomass-to-SAF pre-engineering technical services. WP = Work Package. FEED = Front-End Engineering and Design.

8. Conclusions

Fischer–Tropsch synthesis is not circular by itself. It is the hydrocarbon conversion engine at the centre of a system that must be designed, validated, and operated as a circular economy platform in order to support any credible claim that MSW-derived or biomass-derived SAF is sustainable, low-carbon, and certifiable. The evidence assembled in this paper establishes four controlling conclusions.

First, the FT reaction stoichiometrically produces water as a co-product, and that water carries the majority of nitrogen contamination from biomass- and MSW-derived syngas in the form of tertiary alkylamines that partition 89% into the aqueous phase (Voeten et al., 2024). Any circular SAF claim that does not include an engineered FT water treatment system is incomplete.

Second, integrated two-stage gasification with upstream recycling achieves the best environmental performance among the seven MSW-to-biofuel pathways evaluated by comparative lifecycle assessment (Raj et al., 2026), with an avoided GWP of $-1,095$ kg CO₂ eq per tonne of MSW. This result is pathway-specific and feedstock-dependent and requires primary feedstock characterization for each regional application.

Third, FT-derived SAF — which is predominantly paraffinic and contains less than 1% aromatic compounds — does not produce sufficient NBR O-ring swelling to maintain sealing integrity in legacy aircraft fuel systems at blend fractions above 50%v (Faulhaber et al., 2023; Luning Prak et al., 2025). This is a system-level material compatibility constraint, not a combustion chemistry constraint. Resolution requires either a blend composition that achieves conventional swell through cycloaromatic or aromatic dopant addition, or a multi-year ASTM D4054 approval process for each proposed fuel composition.

Fourth, the aviation industry’s announced SAF capacity for 2024 achieved only a 24% on-time realization rate globally (Martulli et al., 2025), with Fischer–Tropsch projects specifically impeded by technical and operational barriers. The primary barrier is not financing — it is the absence of a validated technical system boundary. Projects that advance without resolved feedstock qualification, syngas cleaning specifications, water management design, material compatibility testing, and carbon intensity verification encounter these problems at the engineering and permitting stage.

Cobeal’s proposed role is to construct and deliver the technical system boundary — through Tier 1, Tier 2, and Tier 3 pre-engineering services — that transforms a regional MSW or biomass feedstock opportunity into a qualified, testable, and engineering-ready SAF development basis. This scope addresses the structural cause of the SAF realization gap and positions Cobeal as the technical discipline layer that aviation-sector stakeholders require before capital is committed to engineering, permitting, technology licensing, or EPC procurement.

References

1. Boerboom, L., Gangoli Rao, A., Grewe, V., & Yin, F. (2025). A comprehensive well-to-wake climate impact assessment of sustainable aviation fuel. *Scientific Reports*, 15, 31966. <https://doi.org/10.1038/s41598-025-13445-x>
2. Faulhaber, C., Borland, C., Boehm, R., & Heyne, J. (2023). Measurements of nitrile rubber absorption of hydrocarbons: trends for sustainable aviation fuel compatibility. *Energy & Fuels*, 37, 9207–9219. <https://doi.org/10.1021/acs.energyfuels.3c00781>
3. Luning Prak, D.J., Graham, D., Hunt, K., Evans, M., Dickerson, T., Slager, J., & Cowart, J.S. (2025). Determining the swelling behavior and tensile strengths of commercially produced Buna-N O-rings and stereolithographic additively manufactured O-rings after exposure to mixtures containing jet fuels, synthetic fuels, and fuel surrogate. *ACS Omega*, 10, 33777–33787. <https://doi.org/10.1021/acsomega.5c04803>
4. Martulli, A., Brandt, K., Allroggen, F., & Malina, R. (2025). The potential scale-up of sustainable aviation fuels production capacity to meet global and EU policy targets. *Nature Communications*, 16, 11619. <https://doi.org/10.1038/s41467-025-66686-9>
5. Raj, R.S., Jain, S., Sharma, A.K., & Singh, V.P. (2026). Life cycle assessment of MSW-to-biofuel conversion pathways: a comparative analysis. *Scientific Reports*, 16, 8932. <https://doi.org/10.1038/s41598-025-32082-y>
6. Velocys Technologies Ltd. (2016). Methods of making purified water from the Fischer-Tropsch process. International Patent WO 2016/044348 A1. World Intellectual Property Organization.
7. Voeten, R.L.C., Hendriks, F., & Bezemer, G.L. (2024). Fischer–Tropsch synthesis for the production of sustainable aviation fuel: formation of tertiary amines from ammonia contaminants. *ACS Omega*, 9, 31974–31985. <https://doi.org/10.1021/acsomega.4c03734>
8. Worley Consulting & IATA Sustainability and Economics. (2025). Global feedstock assessment for SAF production: outlook to 2050. International Air Transport Association.