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PERSPECTIVE

Bridging Refinery and Biorefinery: Modular Hydrotreating Pathways for Co-Processing Refractory Streams and Bio-Oils

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Abstract

Integrating biomass-derived oils into existing petroleum refineries is one of the fastest routes toward large-scale deployment of renewable liquid fuels. Yet co-processing bio-oils with refractory fossil streams, such as vacuum gas oil, cycle oils or coker gas oils, poses persistent hurdles: their high oxygen content, thermal instability and heteroatom-rich matrices accelerate catalyst fouling and drive hydrogen consumption. This Perspective argues that a modular hydrotreating strategy, in which tailored pretreatment, grading and active catalyst beds are arranged as interchangeable cartridges, offers a pragmatic path to bridge refinery and biorefinery operations. Drawing from recent continuous slurry hydrocracking, fixed-bed co-hydrotreating and digital-twin studies, it outlines how modular bed architecture, advanced slurry catalysts and adaptive control schemes could unlock feed flexibility while extending catalyst life by 40% and cutting greenhouse-gas footprints by 25% relative to standalone units. Finally, a short-term R&D agenda linking accelerated deactivation testing, machine-learning-guided feed classification and life-cycle assessment benchmarks aimed is proposed at meeting 2030 renewable-diesel targets.

Keywords: co-processing, hydrotreating, bio-oil, vacuum gas oil, modular refinery, catalyst deactivation.

1 Snapshot: The Feedstock Convergence Challenge

Ultra-low-sulfur fuel regulations and the rapid growth of hydrotreated vegetable oil (HVO) capacity have pushed refiners to search for hybrid feeds that blend fossil and renewable carbon. Mexico alone expects bio-oil availability to reach 0.9 Mt per year by 2030, yet more than half of domestic hydrotreating capacity is already committed to desulfurizing refractory coker and cycle oils. Attempting to run these oxygen-rich bio-oils together with aromatic-rich refinery cuts in conventional trickle-bed reactors often results in pressure-drop excursions, rapid NiMo/CoMo deactivation and unscheduled shutdowns [5]. Continuous slurry hydrocracking trials demonstrate

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that if catalyst residence time and hydrogen-to-oil ratio are decoupled from bed hydrodynamics, co-processing windows expand significantly [1]. These observations motivate a shift from monolithic reactor design toward modular, feed-adaptive architectures.

2 State-of-the-Art in Co-Hydrotreating

Early trickle-bed trials that spiked ≤ 5wt.% mildly stabilized fast-pyrolysis oil (FP-oil) into vacuum gas oil (VGO) proved the basic chemistry (>85% deoxygenation and near-quantitative sulfur removal) but only at the cost of a 30–40 % hike in hydrogen demand and frequent pressure-drop excursions [7]. This hydrogen penalty triggered a pivot toward slurry hydrocracking, where dispersed Mo-sulfide nanoparticles circulate with the oil. In a 100-h continuous campaign, Bergvall and co-worker co-fed 20wt.% FP-oil with VGO without loss of throughput; catalyst attrition was the main constraint, not fouling, and total oxygen was cut below 2wt.% in the diesel fraction [1]. Follow-up work demonstrated that adding a heavy-residue "diluent" widens the operating window even further, enabling 50 h campaigns at 420°C before regeneration [2].

A complementary stream of research tackles hydrothermal-liquefaction (HTL) biocrudes, whose high nitrogen and asphaltene levels accelerate conventional NiMo deactivation. Badoga et al. [7] showed that blending just 10 wt.% HTL oil with VGO in a fixed-bed hydrocracker doubles the deactivation rate unless a guard bed is installed ahead of the active catalyst. More recently, Alvarez-Majmutov et al. [11] achieved stable co-hydrotreating of algae-derived HTL oil at 15 wt. % by employing sequential hydrotreating–hydrocracking and on-line feed desalting, retaining 68 % of the biogenic carbon in the diesel fraction. These advances dovetail with mild hydrotreatment pretreatments that remove 40–60 % of the heteroatoms at <350 °C, dramatically improving downstream catalyst life [3].

Beyond bench and pilot scales, techno-economic analyses (TEAs) now quantify the business case for co-processing. A recent TEA of a 40,000 bbl per day Gulf-coast refinery concluded that swapping 10 wt. % of VGO for algal HTL oil lifts total fuel production costs by only 3–5 %, provided hydrogen is sourced at ≤ US $1.50per kg and spent catalysts are regenerated on-site [10]. Sensitivity runs further highlight that catalyst replacement frequency and high-pressure separator capacity dominate operating expenses, underscoring the importance of deactivation-resistant grading beds and flexible gas-handling schemes.

Finally, the review literature has matured: Lindfors et al. [9] consolidate lessons from > 120 pilot campaigns, emphasizing three universal success factors: phosphorus/alkali abatement, feed stabilization, and dynamic temperature profiling along the bed.

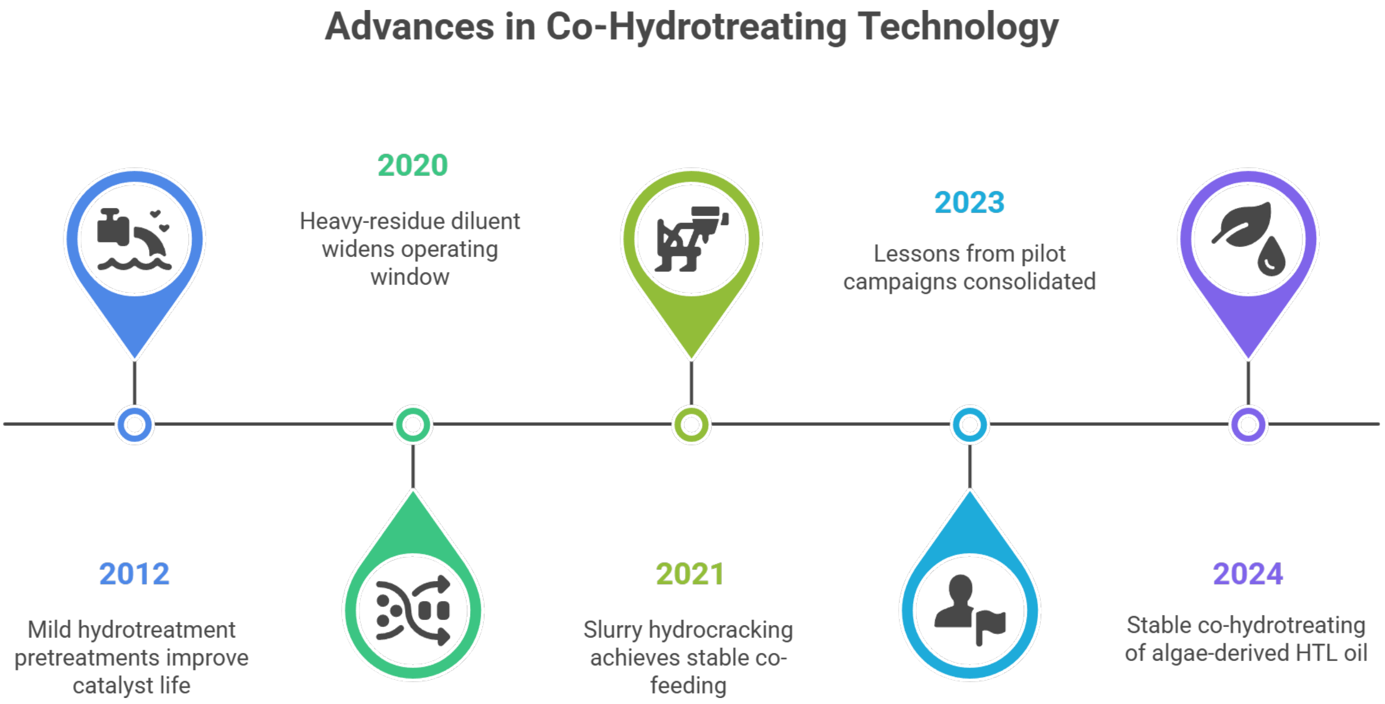

Figure 1. Advances in co-hydrotreating technology.

Reduced emissions Bio-oil integration can significantly lower greenhouse gas emissions in refining processes.

Renewable resource Bio-oil offers a sustainable alternative to fossil fuels in refinery operations.

Potential cost savings Bio-oil could lead to long-term cost reductions in refinery fuel consumption.

Thermal mismatch Bio-oil's low cracking temperature clashes with high-temperature VGO processing.

Multiphase issues Water and solids in bio-oil complicate liquid distribution in reactors.

Catalyst problems Bio-oil's nitrogen and metals accelerate catalyst deactivation and fouling.

Digital gaps Lack of real-time data hinders effective process control and optimization.

Figure 2. Bio-oil integration in refineries.

Collectively, these insights move the field from proof-of-concept toward deployable process packages yet also expose the remaining bottlenecks that Section 3 will dissect. A summary of technological advances in co-hydroprocessing overtime is shown in Figure 1.

3 Technical Gaps Hindering Scale-Up

Although small-scale trials have demonstrated that bio-oil fractions can, in principle, be hydro-treated alongside refractory vacuum gas oils (VGOs), the leap to full-rate refinery operation has exposed a set of stubborn technical discontinuities as shown in Figure 2. Laboratory studies show that the oxygen-rich, water-laden matrix of fast-pyrolysis oils promotes early catalyst deactivation and pressure-drop excursions even at blend levels below 10 wt.% [8]. Pilot campaigns that raised the bio-oil share to 20 wt.% required frequent reactor warm-ups to clear fouling, eroding the touted energy benefits [4]. Comprehensive reviews now converge on four interlocking bottlenecks (thermal–chemical mismatch,

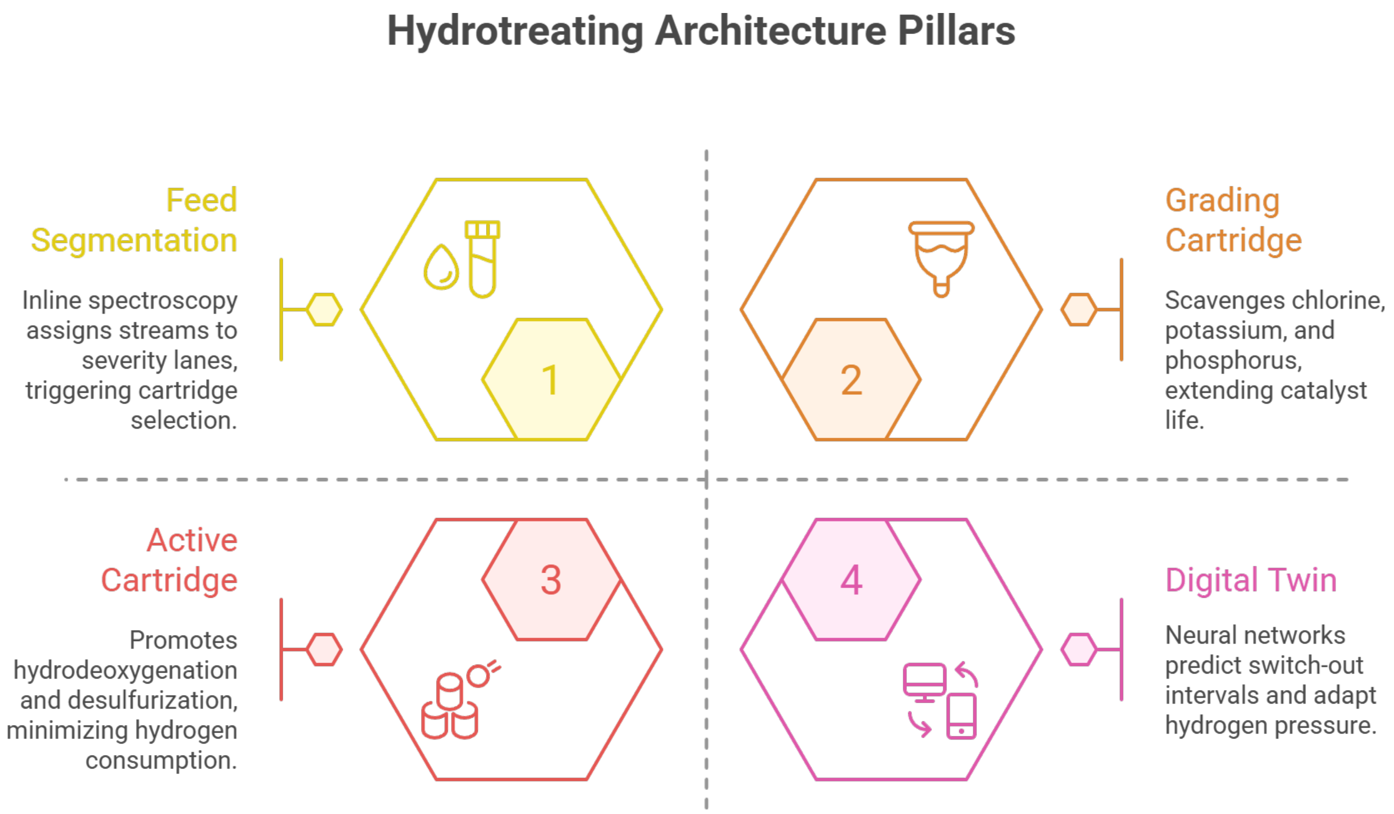

Figure 3. Hydrotreating architecture pillars.

multiphase mal-distribution, shortened catalyst life, and the absence of real-time process intelligence) that collectively stall commercial deployment [9]. The following bullets unpack each barrier and quantify its practical impact on plant reliability and economics.

- **Thermal-chemical mismatch**. Bio-oils crack and polymerize at <350 °C, whereas refractory vacuum gas oil requires >380 °C for deep desulfurization; modular staging is needed to reconcile kinetics.
- **Multiphase hydrodynamics**. Water and solids entrained in bio-oils disrupt liquid distribution, demanding reactor internals or slurry operation [4].
- **Catalyst durability**. Conventional sulfided NiMo catalysts suffer accelerated sulfidation loss and coke depositions when nitrogen >1 wt. % and metals >30 ppm.
- **Digital integration**. Lack of real-time feed fingerprinting and deactivation models hampers proactive control [6].

4 A Modular Hydrotreating Roadmap

To convert those liabilities into manageable engineering variables, a modular hydrotreating architecture inspired by recent slurry-phase and guard-bed demonstrations [2] is advocated, as shown in Figure 3. The concept treats hydrotreating not as a single, monolithic reaction zone but as a configurable sequence of cartridges, each tuned to a well-bounded severity window and protected by data-driven control loops. Early techno-economic assessments suggest that such staging can cut hydrogen penalties by up to 25% and extend catalyst campaigns by 2000 h, provided the system is paired with near-infrared feed fingerprinting and physics-informed neural-network twins [11]. The four pillars outlined below chart a pragmatic R&D agenda that aligns with refinery turnaround cycles while accelerating the integration of renewable carbon.

- **Pillar 1.** Feed Segmentation: Inline near-infrared spectroscopy assigns each incoming stream to predefined severity "lanes," triggering appropriate cartridge selection.
- **Pillar 2.** Grading Cartridge: Dispersed Mo-sulfide slurry or embedded guard beds scavenge chlorine, potassium and phosphorus, extending downstream catalyst life by >2kh [2].
- **Pillar 3.** Active Cartridge: High-surface-area NiMo/γ-Al_2O_3 with hierarchical pores promotes simultaneous hydrodeoxygenation and

desulfurization while minimizing hydrogen consumption via staged quench.

- **Pillar 4.** Digital Twin: Physics-informed neural networks fed by accelerated aging data predict optimal switch-out intervals and adapt hydrogen partial pressure in real time.

5 Conclusions and Call to Action

Modular hydrotreating offers a technically viable bridge between refinery and biorefinery paradigms. By decoupling pretreatment, impurity capture and deep upgrading in configurable cartridges, refiners can harvest renewable carbon without sacrificing throughput or catalyst longevity. Collaborative pilot campaigns that integrate accelerated deactivation matrices, machine-learning control loops and rigorous life-cycle assessment are urgently needed so that commercial units meeting 2030 renewable-diesel targets can emerge within the decade.

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Conflicts of Interest

The author declares no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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