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From PFAD Conversion to Refinery Qualification: Catalyst Lifetime, Hydrogen Efficiency and Carbon Integrity in Renewable-Diesel Co-Processing

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ABSTRACT

Palm fatty acid distillate (PFAD) is an attractive free-fatty-acid-rich intermediate for producing paraffinic fuels, but laboratory conversion does not establish reliable performance in an existing petroleum refinery. This critical qualitative literature review examines peer-reviewed research from 2020 to 2026 on PFAD composition, competing deoxygenation chemistry, catalyst deactivation, hydrogen use, refinery co-processing, product qualification, and lifecycle accounting. The thematic synthesis identifies six interlocking constraints: feedstock variability and adsorption-driven side reactions; the carbon-retention versus hydrogen-demand trade-off; uncertainty in catalyst durability; interactions with fossil-stream hydrotreating; hydrogen and thermal-system integration; and contested allocation of upstream palm-oil emissions. It proposes a Feedstock-Catalyst-Hydrogen-Refinery-Carbon (FCHRC) Readiness Framework and a staged evidence scorecard for testing compatibility before deployment. The central finding is conditional: PFAD-to-hydrocarbon conversion has been demonstrated in several settings, whereas long-term, refinery-specific co-processing reliability and unqualified low-carbon status cannot be inferred from high short-run conversion or yield. Future studies should combine representative PFAD characterization, long-duration fixed-bed testing, mass and hydrogen balances, petroleum co-feed benchmarks, appropriate fuel specifications, and transparent consequential lifecycle scenarios. The framework is conceptual and not presented as a field-validated technology.

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JEL Classification Codes: Q42; Q56; L71; O33; C61.

Introduction

Refinery Transformation Demands More Than a Renewable Feedstock

Petroleum refineries face an increasingly complex transition. Their existing reactors, storage systems, hydrogen networks and product-distribution infrastructure represent capital-intensive assets, while fuel consumers and policy systems increasingly demand reductions in lifecycle greenhouse-gas emissions. Co-processing biogenic material with petroleum feedstocks may offer a practical transitional route, but it creates engineering challenges that cannot be resolved by the simple statement that a vegetable oil is renewable. A hydrotreater originally designed to remove sulfur and nitrogen from petroleum distillate also has to accommodate oxygen-rich molecules, heat release, additional water and carbon oxides, and changes in catalyst exposure. Recent refinery studies show that the environmental and technical value of co-processing depends on precisely these configuration-specific conditions.

Hydroprocessed esters and fatty acids, commonly discussed through the HEFA or hydrotreated vegetable oil (HVO) family of routes, can yield paraffinic hydrocarbon products. These are chemically distinct from fatty acid methyl ester (FAME) biodiesel because their oxygen atoms have been removed and hydrocarbon composition rather than ester composition defines their use. Yet names such as green diesel, renewable diesel and bio-hydrogenated diesel are not sufficient indicators of product quality. A liquid with an attractive diesel-boiling fraction may still require further finishing, fractionation, stability testing or hydroisomerization before it satisfies the demands of a particular distribution or engine system. Contemporary catalyst and fuel reviews underline the need to follow the entire production chain rather than presenting a single reactor yield as product qualification.

Why Palm Fatty Acid Distillate is a Special Case

Palm fatty acid distillate is generated during the physical refining of crude palm oil, where volatile fatty acids and associated minor components are separated from the principal refined oil stream. Its relatively high free-fatty-acid content makes it different from a largely triglyceride-based edible oil. The distribution of palmitic, oleic and other fatty acids matters because chain length, degree of unsaturation and acid concentration influence reaction selectivity, hydrogenation needs and the tendency of reactive species to occupy catalytic surface sites. PFAD is therefore not

interchangeable with generic vegetable oil, waste cooking oil or animal fat without appropriate compositional comparison. Studies of direct PFAD conversion and mixed PFAD-palm-oil feeds explicitly demonstrate that feed identity can alter the distribution of diesel-range hydrocarbons and oxygenated intermediates.

The feedstock is sometimes described as a waste with no alternative use, but this can conceal significant economic relationships. PFAD has existing applications and a market value; diverting it into fuel production can change the raw-material mix available to other users. Its classification as waste, residue, by-product or economically allocated co-product is therefore not merely an accounting label. In lifecycle assessment, the choice determines which upstream palm cultivation and refining burdens are attributed to fuel and what displacement of alternative materials is considered. Quantitative PFAD lifecycle research has shown that reported emissions advantages are sensitive to these decisions, while later palm-refining comparisons illustrate how operating configuration and feedstock status can change environmental conclusions.

The Overlooked Space Between Conversion and Industrial Readiness

The empirical catalyst literature is highly productive. Investigations have achieved liquid hydrocarbon formation from PFAD using supported nickel and cobalt, bimetallic combinations, phosphides, zeolitic supports and metal-organic-framework-derived materials. These experiments establish credible molecular opportunities, but the endpoints frequently emphasize conversion, selectivity or reuse over a modest number of cycles. They do not all report an equivalent liquid-yield denominator, hydrogen input, carbon balance, feed pretreatment burden or extended continuous operating period. Results from hydrogen-free nitrogen atmospheres are particularly important to distinguish from high-pressure hydrodeoxygenation: both can make hydrocarbons, but their oxygen-removal mechanisms and process-system implications are not identical.

Kim and colleagues' mixed-feed investigation offers a caution against a simple more-is-better view of PFAD substitution. Increasing PFAD concentration was associated with stronger adsorption of free-fatty-acid intermediates and greater formation of fatty alcohols, wax esters and ketones under the tested Pt/Al2O3 conditions. The paper suggested a feed blending boundary for its specific experimental system, not a universally safe PFAD blending rule for all catalysts or petroleum feedstocks. An economically useful co-processing strategy must therefore identify a formulation-specific operating window rather than extrapolate from maximum laboratory yield (Kim et al., 2024). The study also illustrates how side-product analysis can reveal failure mechanisms hidden by gross conversion percentages.

Research Questions and Contribution

This review asks seven questions concerning feedstock quality, reaction pathways, catalyst survival, the distinction between dedicated and petroleum co-processing, hydrogen and fuel finishing, lifecycle attribution, and minimum evidence for industrial qualification. The aim is not to identify an inherently superior chemical pathway by counting favorable reported results. It is to examine the mechanisms and trade-offs that determine which process becomes credible in a particular refinery setting, with its actual products and emissions consequences. By bringing together studies of PFAD catalysis, model fatty acids, refinery equipment and lifecycle assessment, the review creates an integrated interpretive basis for industrial decisions.

Figure 1 outlines the system boundary used in the analysis. It follows PFAD from characterization and conditioning through catalytic conversion, hydrogen supply, refinery integration and finished-product verification. The figure also marks the governance and accounting decisions that must be resolved before a process can properly be called low-carbon; it is a conceptual map and not a demonstration of an operational refinery co-processing line.

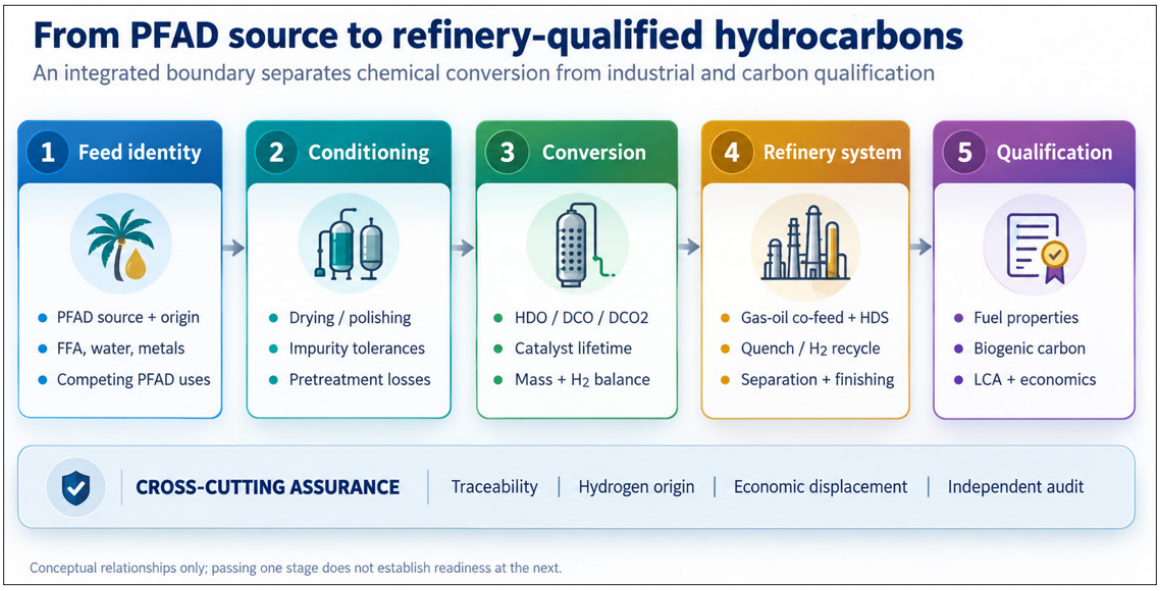


Figure 1: PFAD-to-refinery system boundary, including feed and carbon-assurance gates. Source: Authorial conceptual synthesis; no measured field performance is implied.

The arrows in Figure 1 are deliberately conditional. Material suitability at one stage does not automatically secure acceptability at the next: a clean, low-phosphorus feed can still create a strongly adsorbed intermediate; an active catalyst can still demand excessive hydrogen; and an acceptable diesel fraction can still have an unfavorable lifecycle footprint. This separation of scientific claims permits positive experimental findings to be acknowledged without overstating industrial readiness. Similar distinctions arise in the refinery-oriented modelling and economic literature.

Literature Review: Conceptual and Theoretical Foundations

Lipid Chemistry, Feedstock Heterogeneity and Preconditioning

PFAD composition is shaped by crude oil quality, refining severity, deodorization conditions and subsequent handling. A feed rich in free acids introduces carboxyl groups directly to catalytic sites, whereas triglyceride-rich feeds must pass through intermediate transformations involving glyceride cleavage and oxygenate formation. Storage and oxidation can generate additional polar species, while water, metals, phospholipids and other impurities affect pretreatment and conversion. The technical objective of preconditioning is not to eliminate all variation, which may be economically impossible, but to define a composition envelope within which kinetics, corrosion risk and catalyst poisoning remain manageable.

Industrial feed conditioning can include settling, filtration, water reduction, degumming, adsorptive removal of metals and phosphorus, or alternative treatment stages appropriate to the actual contaminant profile. These processes add equipment, chemicals, energy use and material losses; consequently, a low quoted price per tonne of PFAD does not establish a low effective price at the hydrotreater inlet. A study using clean or commercial-grade acid feed may offer useful catalyst chemistry while understating the pretreatment costs of heterogeneous real PFAD. The distinction is particularly important when comparing emerging catalysts with industrial sulfided beds, because differences in sample purity may explain apparent advantages.

An additional practical distinction concerns whether a feed-quality envelope is demonstrated by measurements or inferred from a nominal purchase specification. Recent reviews of catalytic HVO production emphasise that reactor configuration, catalyst family and the composition of real oils interact with pretreatment and finishing requirements. Accordingly, a meaningful feed envelope should be established by controlled variation of water, phosphorus, alkali metals and free-acid content, with the measured retention of activity documented at each exposure level.

Oxygen removal involves competing carbon and hydrogen balances

Long-chain fatty acids can be converted to paraffinic hydrocarbons through several routes. Hydrodeoxygenation removes oxygen primarily as water and can preserve the fatty-acid carbon number; decarboxylation releases carbon dioxide and shortens the hydrocarbon chain by one carbon; decarbonylation releases carbon monoxide, also typically shortening the chain. Actual feeds add unsaturated double bonds, which require hydrogenation, and reaction networks can involve aldehydes, alcohols, esters, ketones and cracked fractions. These pathways should be evaluated through carbon yield, gas analysis, hydrogen consumption and product distribution together, not reduced to a single percentage labelled deoxygenation efficiency.

For saturated palmitic acid as an illustrative model, idealized net balances can be written as follows. The balances separate chemistry, not actual refinery consumption, because real reactors also consume hydrogen through saturation, desulfurization, gas reactions and other steps.

HDO: $C_{16}H_{32}O_2 + 3\ H_2 \rightarrow C_{16}H_{34} + 2\ H_2O$

DCO_2: $C_{16}H_{32}O_2 \rightarrow C_{15}H_{32} + CO_2$

DCO: $C_{16}H_{32}O_2 + H_2 \rightarrow C_{15}H_{32} + CO + H_2O$

These idealised net equations concern saturated palmitic acid and are not measured refinery yields. Real conversion also involves parallel reactions and must be evaluated through complete hydrogen, oxygen and carbon balances.

Hydrodeoxygenation retains sixteen carbon atoms in the alkane but requires hydrogen for oxygen removal as water in the idealized balance. Decarboxylation can remove oxygen without external molecular hydrogen in that idealized expression, while sacrificing one carbon atom as CO2. Decarbonylation produces CO and water and consumes hydrogen in the simplified saturated-acid reaction. These are not interchangeable environmental outcomes because CO, CO2, water and other gases may trigger additional treatment, methanation or hydrogen-system effects. Apparent hydrogen-saving performance must therefore be interpreted alongside liquid carbon recovery and total plant hydrogen demand.

Figure 2 presents this reaction-level choice in a format that can be compared with the process-level evaluation. It differentiates desired paraffin formation from secondary pathways producing alcohols, ketones, wax esters, gases or excessive cracking, and emphasizes that the proportions depend on feed and catalyst environment.

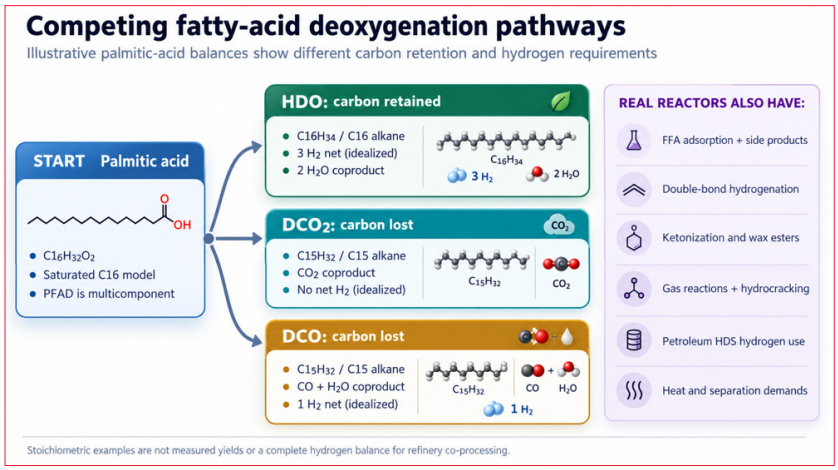


Figure 2: Idealized deoxygenation pathways and operational factors affecting total hydrogen and carbon balances. Source: Authorial conceptual synthesis; no measured field performance is implied

The reaction map in Figure 2 explains why the n-alkane carbon-number pattern can be informative but cannot independently quantify hydrogen efficiency. Production dominated by C15 and C17 from C16 and C18 acids suggests greater importance of carbon-losing routes, while C16 and C18 can support a carbon-retaining interpretation when the analytical basis is established. Yet parallel hydrogenation, cracking and hydrogen transfer complicate simple inference. Studies of palmitic and oleic acid on Ni/Mo materials, phosphides and modified supports show how strongly active-site properties can alter selectivity.

Catalyst chemistry and the durability problem

Sulfided NiMo and CoMo systems remain important reference technologies because petroleum refineries already use closely related catalysts for hydrodesulfurization. In lipid-rich feeds, however, oxygen-rich molecules, water and changes in sulfur chemical potential can alter catalyst surfaces. Reduced nickel, cobalt and noble-metal systems offer different oxygen-removal and hydrogenation tendencies, while phosphides, zeolites and bifunctional materials attempt to influence adsorption and cracking through metal-support chemistry. Reviews emphasize that activity is inseparable from the reaction environment: increasing the number of acid sites or metal sites can improve one product selectivity while accelerating coke production or secondary cracking.

Mechanistic model-compound studies provide unusually clear illustrations. Palmitic acid hydrodeoxygenation over sulfided NiMo has been studied with microkinetic attention to mass transport and intermediate concentration, while nickel catalysts on modified supports demonstrate how defect structures and metal-support interactions can influence performance. These are valuable findings about pathways and active-site behavior, not direct rankings of full PFAD feeds in a petroleum hydrotreater. Experiments using hydrothermal aqueous media, in particular, should be transferred cautiously to anhydrous or hydrocarbon-rich reactor conditions.

A directly relevant PFAD investigation used La-modified zeolite beta under hydrogen-containing conditions and reported a predominance of C16 products alongside differences in coking behaviour between test atmospheres. The study reinforces the chemical importance of catalyst acidity, hydrogen atmosphere and experimental conditions, but its short experimental period and reuse tests should be interpreted as preliminary durability evidence rather than as industrial catalyst service life. Such evidence complements, rather than replaces, trials involving petroleum contaminants and continuous refinery co-feed.

Catalyst durability has multiple failure modes. Phosphorus, sodium, potassium, iron and related species may poison sites or accumulate within catalyst bodies; coke and adsorbed heavy compounds can block access; sintering changes metal dispersion; and changes in active-phase sulfidity can reduce performance. Examination of a catalyst recovered from an operating renewable-fuel refinery provided direct evidence that contamination is not a theoretical inconvenience, with differential movement and activity effects of metal and phosphorus species. This is a stronger durability warning than a fresh-catalyst batch test showing high conversion.

The distinction between fresh-catalyst activity and service-exposed performance has been made particularly concrete in an industrial green-hydrotreater investigation. Nejadmoghadam et al. (2025) assessed sulfided catalyst samples exposed in an operating unit, finding potassium, phosphorus and sodium contamination and different tendencies toward site poisoning and coke-related blockage across catalysts and bare supports. Washing did not restore every tested active catalyst, demonstrating why regeneration must be a measured result rather than an assumed recovery step. Although the work does not establish a PFAD-specific service interval, it supplies directly relevant industrial evidence for the durability gate proposed here.

Dedicated hydroprocessing is not petroleum co-processing

Dedicated lipid hydroprocessing can be designed around fatty-acid or triglyceride conversion, including suitable staging of deoxygenation, gas removal and hydroisomerization. Co-processing in an established petroleum hydrotreater is a different experiment: the same bed may need to remove sulfur from gas oil while reducing oxygen from PFAD, and the chemical interaction can change available hydrogen, gas composition and operating temperature. Evidence from co-processing vegetable oil, used cooking oil, jatropha oil and alternative biocrudes indicates that refinery compatibility must be assessed using the actual fossil feed, catalyst state and unit constraints.

Pilot-scale work with microbial triacylglyceride-derived oils illustrates the additional evidence needed to progress beyond molecular conversion. Dimitriadis et al. (2024) evaluated hydrotreatment across technology-readiness stages, included product fractionation and compared the resulting fuels with application-specific specifications; this is an adjacent-feedstock illustration of qualification practice, not an experimental demonstration of PFAD co-processing. Its relevance is methodological: a defensible scale-up claim requires product validation, repeatable balances and carefully matched process operating conditions.

Furthermore, raw PFAD cannot be assumed to mimic refined palm oil in co-processing trials. Free-acid concentration, adsorption and impurity exposure may be particularly consequential in mixtures with hydrocarbon middle distillate, which have very different polarity and sulfur composition from laboratory refined-glyceride blends. A result obtained with PFAD diluted in refined palm oil does not demonstrate that the same ratio is suitable when PFAD is added to a petroleum gas-oil feed. The proper experiment must directly assess sulfur removal, oxygen removal, hydrogen availability, heat release, stable liquid products and catalyst response under the targeted petroleum co-feed.

Hydrogen systems, heat management and finished fuels

Hydrogen enters at more than one level. It enables initial saturation, oxygen removal, desulfurization, hydrogenation of side intermediates and selected product-finishing reactions. Recycle gases may also contain methane, water vapor, CO and CO2, while the hydroprocessing bed releases heat that must be managed to preserve stability and avoid excessive cracking. Industrial reactor modelling shows that multibed design, interbed quench, transfer limitations and inlet temperature can control temperature excursions and yield. Economic simulation of integrated renewable diesel and hydrogen production likewise demonstrates that alternative hydrogen-production systems create different capital and operating trade-offs.

Finished paraffins can have attractive cetane quality but unfavorable cold-flow properties when a high proportion of linear long-chain hydrocarbons is retained. Hydroisomerization can improve cold-flow performance while risking cracking, lower

distillate recovery and altered fuel properties. Specific reactor products must therefore be analyzed for relevant diesel standards, contaminant limits, distillation behavior, density, viscosity, cetane properties and stability. FAME standards such as ASTM D6751 or EN 14214 are not equivalent substitutes for requirements applicable to hydrocarbon renewable diesel. This distinction is important when literature reports broad fuel compliance based on chemically inappropriate comparisons.

Fuel qualification must also reflect the properties of the final blend rather than only those of the neat renewable stream. McCormick et al. (2024) measured high-level combinations of renewable diesel, FAME biodiesel and petroleum diesel and demonstrated that blending can raise questions about viscosity, volatility, cold flow, flash point and other product attributes. Their samples were not PFAD-derived, so the transferable lesson is a testing requirement rather than a direct PFAD performance result: each intended finished fuel and blend ratio requires an appropriately selected specification and measured property portfolio. These obligations are distinct from the catalyst laboratory's conversion and selectivity calculations.

Lifecycle and Economic Foundations

Lifecycle greenhouse-gas intensity depends on system boundary, feedstock classification, palm cultivation impacts, alternative PFAD use, hydrogen source, process utilities, coproduct allocation and land-use assumptions. In a foundational 2020 assessment, PFAD-derived renewable diesel appeared advantageous under some by-product allocation choices yet could lose its claimed emissions advantage under alternative coproduct and land-use assumptions. This is not a contradiction to be averaged away: it demonstrates that the environmental result is conditional on the defined economic and physical counterfactual.

Later lifecycle and cost studies reinforce the same methodological lesson. Studies involving palm refining by-products, waste oils and alternative processing modes produce different footprints and cost structures depending on energy use, recycle, plant size and feedstock attribution. Hydrogen pathways deserve explicit carbon-accounting treatment because hydrogen generated from natural gas without effective emission mitigation does not have the same footprint as hydrogen generated with demonstrably lower emissions. A process that becomes cheaper because of a favorable feedstock credit or subsidy may not become chemically superior or environmentally lower impact

Methodology: A Critical Qualitative Literature Review

Review Orientation

This article adopts a critical interpretive qualitative literature review rather than a systematic literature review (SLR). The purpose is to compare mechanisms, evaluate competing explanations, expose inferential overreach and construct an integrated framework for refinery qualification. It does not use PRISMA counts, statistical meta-analysis, or a claim to have found every publication on PFAD chemistry. Published quantitative results are described in the conditions under which they were observed rather than pooled into a single universal activity, yield or greenhouse-gas estimate. This choice is particularly important when papers report different yield denominators, batch and continuous reactors, solvent use, hydrogen pressure and catalyst exposure durations

Purposive Evidence Selection

Literature was selected purposively for relevance to six connected bodies of work: PFAD-specific catalytic conversion, model fatty-acid mechanisms, catalyst deactivation and pretreatment, refinery co-processing and operation, hydrogen and product finishing, and lifecycle or techno-economic assessment. The target temporal window is 2020 through October 2026, and journal sources have identifiable DOI records. Palm-specific work anchors claims about feed chemistry; experiments using other plant oils, stearic or oleic acid, and hydrothermal biocrudes provide carefully bounded mechanistic analogies. Research with non-PFAD feeds is not presented as if it directly validates PFAD refinery operation (Lee et al., 2021; Volonterio et al., 2024; Badoga et al., 2020).

Critical Coding and Evidence status

The analytical comparison asks what was actually fed, what was measured, which reactor operated, how catalyst activity changed, and whether downstream product and carbon claims were independently tested. Six themes were constructed around mechanisms rather than simply listing technologies. Each conclusion is classified implicitly as demonstrated in a cited study, transferable with qualifications from an adjacent system, or proposed for future PFAD qualification. Rival explanations are retained. For example, yield loss attributed to a catalyst may also involve mass transfer, deactivation or changed crude feed; reported emissions savings may also reflect feedstock allocation rather than physical reduction in fuel production emissions (Zula et al., 2023; Arora et al., 2021; Xu et al., 2020).

Reflexivity and Limitations of Inference

As an interpretive review, article choice and synthesis can reflect the author's emphasis on industrial reliability and transparent carbon accounting. Publication bias may favor high-yield catalyst experiments, while negative refinery trials and commercial contaminant data may be unavailable. Accordingly, the review does not assert a numerical optimum PFAD blend fraction, refinery hydrogen intensity, catalyst service interval or emissions saving applicable to all plants. Such quantities require site-specific feed analysis, long-duration operation and verified lifecycle inventory. The framework is therefore explicitly testable and conditional rather than a claim of implemented commercial technology.

Results: Six Thematic Findings

Theme I: PFAD Identity and Concentration Jointly Determine Feed Readiness

The first thematic result is that feedstock identity cannot be reduced to a renewable-versus-fossil distinction. PFAD is a processing stream rather than a chemically fixed reagent. Its proportion of free fatty acids, distribution of saturated and unsaturated chains, residual neutral oil, moisture, and trace contaminants may depend on source and processing history. Experiments employing defined feedstocks provide useful evidence about catalytic mechanisms but cannot remove the need to characterize the actual material that a refinery would purchase. A nominal PFAD specification containing only an acid value and a bulk fatty-acid profile leaves several potential catalyst hazards invisible.

A second finding is that increasing concentration creates a nonlinear rather than necessarily proportional catalytic response. Kim et al. (2024) examined PFAD mixed with palm oil and described strongly adsorbed free-fatty-acid species, with changes in alcohols, wax esters and ketones as PFAD content increased under the studied conditions. The inference is not that every catalyst has a common allowable PFAD fraction. It is that free-acid coverage and interaction with other reactive species may cause a practical mixture to depart from simple predictions based on isolated-compound conversion. The observation provides an

especially important experimental design principle for petroleum co-processing, where petroleum hydrocarbons and organosulfur compounds compete within the same reactor environment.

Feed pretreatment is accordingly a process-design variable, not a minor purchase specification. Removing water and catalyst poisons can reduce deactivation risks, yet every polishing step introduces sorbent use, material loss, energy demand, and cost. Highly purified PFAD can perform differently from a low-cost commercial stream, which means catalytic rankings derived from purified material may not preserve their order after industrial feed conditioning. Studies of vegetable-oil quality and hydrotreatment conditioning show how prior processing affects conversion and finished hydrocarbon recovery, although a dedicated PFAD pretreatment threshold still requires validation for each intended catalyst and petroleum feed.

A robust characterization protocol should record at least fatty-acid and neutral-lipid distributions, water, phosphorus, sodium, potassium, calcium, iron, sulfur and relevant solids, together with the analytical methods and detection limits. Not every feed contains each impurity at a harmful concentration, and the list is a proposed assurance screen rather than evidence of universal PFAD contamination. More importantly, limits should be connected to observed catalyst behavior and pretreatment performance instead of selected only because an analytical method can measure them. This would make PFAD purchases, experiments, and eventual supplier guarantees scientifically comparable.

Theme II: Carbon retention, hydrogen consumption and reaction selectivity form a coupled trade-off

The second thematic result is that hydrocarbon production does not uniquely define a conversion pathway. Hydrodeoxygenation of a saturated C16 fatty acid can preserve its carbon number while converting oxygen to water, but the simplified reaction consumes hydrogen. Decarboxylation removes one carbon atom as carbon dioxide, and decarbonylation removes carbon monoxide while leaving a C15 hydrocarbon backbone. Unsaturated acids also require attention to olefin hydrogenation and side reactions. Consequently, equal degrees of oxygen removal can coincide with different liquid carbon recoveries, hydrogen consumption, gas compositions and downstream separation loads.

Experiments on PFAD under hydrogen-free or comparatively hydrogen-lean conditions demonstrate that selective oxygen removal can occur without relying on the same stoichiometric hydrogen demand as conventional HDO. However, they should not be described as proving hydrogen independence for an integrated refinery process. Saturation, desulfurization of a fossil co-feed, stabilization of reactive intermediates, and product finishing can still consume hydrogen elsewhere. Likewise, carbon dioxide generation from decarboxylation and shorter-carbon liquid products affect the interpretation of conversion efficiency. A credible comparison must follow hydrogen and carbon across the complete process boundary, not only across the reactor in which an acid disappears.

Model-molecule studies help identify when pathways compete. Nickel phosphides, supported nickel, sulfided NiMo, and other active phases have been investigated with palmitic or oleic acid, demonstrating sensitivity to catalyst composition and surface properties. Such research supplies mechanistic insights into C-O bond cleavage, hydrogenation and intermediate stability. Yet converting neat palmitic acid in one solvent does not establish performance for a multi-acid PFAD mixture, and the same product profile cannot be expected when the reactor also treats gas oil. This distinction is especially important for results from hydrothermal, transfer-hydrogenation and dry hydrogen-rich conditions, whose hydrogen activities differ.

The literature also cautions against conflating liquid volume yield, hydrocarbon selectivity and carbon efficiency. A liquid fraction may include residual oxygenates, light hydrocarbons and solvent-related materials; selectivity toward the desired carbon chain does not indicate the fraction of original feed carbon retained when decarboxylation is substantial. Authors should report clear mass and carbon balances, recovered gas composition, oxygen content and an explicit basis for product yield. A fair assessment would include molar hydrogen consumption and hydrogen supplied by auxiliary reactions rather than assume that lower external hydrogen pressure proves a more efficient overall production route.

These trade-offs are not intrinsically resolved by a single objective. In one refinery, minimizing marginal hydrogen may justify additional carbon loss to gaseous products; in another, retaining the longer hydrocarbon chain may be economically preferable if low-carbon hydrogen is plentiful. In both cases the resulting diesel fraction must meet the same end-use qualification requirements, and the value of gaseous coproducts should be counted consistently. The appropriate research outcome is therefore a process-specific feasible region bounded by hydrogen availability, carbon retention, product selectivity and lifecycle performance, not a universal ranking of HDO over decarboxylation.

Theme III: Initial catalytic activity is not evidence of acceptable catalyst lifetime

A third finding is that catalyst innovation is often demonstrated through initial activity, while industrial qualification depends on sustained selectivity and manageable replacement costs. PFAD conversion studies have reported promising results with supported Ni/Co formulations, nickel phosphides, zeolite-related materials and MOF-derived porous structures. The availability of multiple active systems is scientifically encouraging, but differences in reactor configuration, feed conditioning, catalyst loading and observation period prevent a simple league table of superior formulations. Even an apparently high-yield system may be operationally unattractive if its activity falls sharply during continuous feed exposure.

Industrial deactivation has several overlapping mechanisms. Metal sites may be poisoned by phosphorus and alkali species; polar intermediates can block accessible surfaces; heavy products and acid-catalysed reactions can promote coke; sintering can reduce dispersed active area; and an active sulfided phase can respond to changes in sulfur and water activity. Arora et al. (2021) analyzed poisoning phenomena in a renewable-oils processing context, supplying evidence that accumulated feed impurities and site access can matter in actual catalyst service. Such findings challenge any generalization from repeated laboratory batch cycles to industrial time-on-stream without characterization of the spent material.

A useful interpretation of catalyst screening is to separate intrinsic reaction selectivity from deactivation under real exposure. In addition to the recovered-catalyst evidence considered by Arora et al. (2021), the service-exposed NiMo and NiW results of Nejadmoghadam et al. (2025) reveal that coke, metals and phosphorus can produce distinct failure patterns. A proposed comparison should therefore include both a time series of selectivity and independent physical and chemical analysis of the

spent catalyst, rather than interpreting every downward conversion trend as the same type of deactivation.

Catalyst chemistry also creates possible design conflicts. Additional acidity may assist hydrocracking or certain dehydration reactions while worsening excessive cracking or coke deposition. Supported nickel catalysts can perform well for saturated fatty acids yet differ from sulfided NiMo catalysts under feeds containing sulfur and nitrogen. Zeolite topology, accessible pore size, metal dispersion and support modification can influence contact with large PFAD components, and data obtained with model fatty acids may isolate only one dimension of a commercial mixture. Mechanistic and review evidence therefore supports a multi-attribute catalyst comparison rather than a single conversion endpoint.

Evidence from related oxygenated streams reinforces the limitations of short duration. Catalytic deoxygenation of waste cooking oil, vegetable lipid mixtures and biomass-derived oils shows that catalyst activity depends on feed heteroatoms, coke propensity and hydrocarbon distribution. Reviews of zeolite-mediated deoxygenation and studies using activated-carbon-supported nickel clarify possible mechanisms but should remain labeled as transferable evidence until tested with representative PFAD and a refinery co-feed. This evidentiary discipline is essential to prevent seemingly compatible catalysts from being recommended on the basis of chemically adjacent but operationally different experiments.

Figure 3 summarizes catalyst durability as a sequence of interacting processes rather than as a single declining activity line. It distinguishes reversible coverage by intermediates from irreversible or slowly reversible site poisoning, fouling, structural transformation and the need for regeneration. These competing explanations require different analytical methods and cannot be reliably diagnosed from product yield alone.

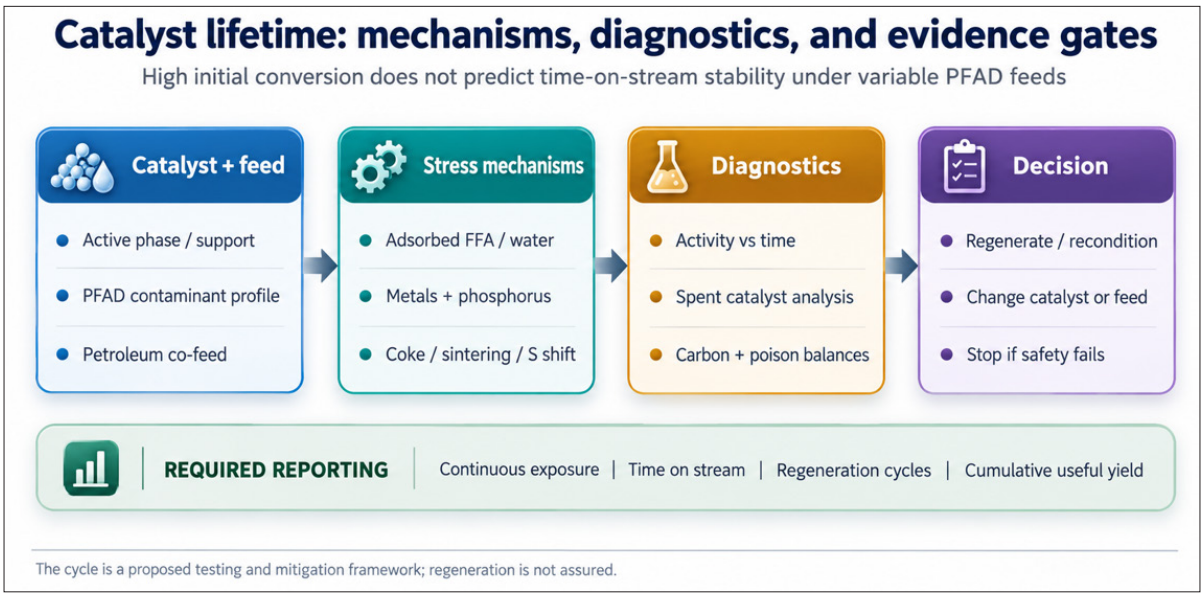


Figure 3: Catalyst durability and deactivation mechanisms, diagnostic evidence and qualification decisions. Source: Authorial conceptual synthesis; no measured field performance is implied.

The arrows in Figure 3 indicate investigation and potential redesign, not assured recovery of a deactivated material. Regeneration might restore selected active sites while leaving irreversible metal contamination or support changes, and a regenerated catalyst should be tested again with the same representative feed. A convincing qualification study should therefore report time-on-stream, catalyst productivity, regeneration history, cumulative liquid yield, impurity balances and post-use material characterization. Where sulfur management is necessary, it must be evaluated jointly with petroleum desulfurization performance rather than treated as a separate laboratory accessory.

Theme IV: Dedicated PFAD Processing and Petroleum Co-Processing Carry Different Risks

The fourth theme concerns transferability across reactor arrangements. Dedicated renewable-oil hydroprocessing may be configured so that oxygen removal, hydrogenation, gas separation and isomerization are optimized for a biogenic feed. A petroleum hydrotreater instead balances hydrodesulfurization, hydrodenitrogenation, aromatic saturation, hydrogen consumption and heat release for an established fossil feed. Introducing PFAD changes molecular adsorption patterns and the products generated in the reaction bed. These shifts can affect the hydrocarbon fuel fraction and the refinery's original sulfur-removal obligations, even where a stand-alone PFAD catalyst looks promising.

Published co-processing demonstrations with used cooking oil, jatropha oil and other oxygenated materials provide useful experimental analogies, but PFAD is not automatically a drop-in equivalent. Acid concentration and feed impurities can differ from those of low-acid vegetable oil, while light-cycle oil and straight-run gas oil have different aromatics and sulfur profiles. The practical study design needs explicit baseline fossil-feed operation followed by representative PFAD additions under matched space velocity, temperature, hydrogen partial pressure and catalyst age. Without this comparison, a change in product quality could be attributed incorrectly to PFAD when it originated in the petroleum co-feed or unit operating severity.

Reactor thermal response is a further readiness constraint. Saturation and oxygen-removal reactions can release substantial heat, and an integrated reactor may experience temperature

gradients or local hot spots that are not captured by a well-mixed laboratory vessel. Industrial multibed simulation studies illustrate the value of quench arrangements, kinetic models, hydrogen recycle and controlled inlet temperature. The transferable lesson is methodological: the viable PFAD fraction must be established together with the actual hydrotreating unit's heat-management capacity, not inherited from a different catalyst, reactor or feed mixture.

Product attribution also becomes complicated in mixed streams. A paraffinic component of biogenic origin may be analytically indistinguishable from a similar petroleum hydrocarbon without appropriate carbon-origin measurement or validated material-balance methods. Certification and lifecycle assessments require transparent accounting for the renewable portion of the co-processed output, including losses into gases and lighter or heavier fractions. Research on integrated HVO processing in an industrial petroleum-refinery scenario demonstrates the importance of drawing a credible operating and carbon-accounting boundary, not solely measuring the volume of fuel leaving the reactor.

The observed research gap is therefore not merely a shortage of chemical conversions; it is a shortage of long-duration PFAD-specific refinery co-feed evidence that jointly documents fossil-fuel upgrading, catalyst stability, hydrogen demand, heat evolution and biogenic-carbon recovery. A concept can be ready for further piloting without having demonstrated full refinery compatibility. The review consequently proposes qualified language such as laboratory-demonstrated conversion, transferable co-processing analogy or field-confirmed integrated operation, with the claim level matching the validation actually conducted.

Theme V: Hydrogen Supply and Fuel Qualification Can Reverse an Apparent Process Advantage

The fifth thematic result is that the hydrogen system can substantially influence environmental and economic performance. Hydrogen is needed for selective carbon-oxygen chemistry, double-bond saturation, petrochemical co-feed upgrading and product finishing. A hypothetical reactor that uses less direct hydrogen for deoxygenation may still require large amounts upstream to generate its reducing agents, downstream for hydroisomerization, or elsewhere in a refinery to preserve product quality. Economic comparisons therefore require a clearly defined marginal hydrogen balance across the facility, not just hydrogen-to-oil ratios reported in a single reactor experiment.

Hydrogen's source affects the credibility of low-carbon claims. A refinery supplied by natural-gas-derived hydrogen without sufficient emissions mitigation has a different life-cycle profile from one using verifiably lower-carbon hydrogen, while the latter may carry higher capital, renewable-power or network costs. Process integration can change the balance again if hydrogen is recycled, coproduct gases are recovered, or steam and electricity are supplied by a common facility. The literature supports comparing explicit hydrogen scenarios, but not asserting that one production route always yields the lowest emissions or cost at every location.

A separate product-quality problem emerges after conversion. High shares of normal paraffins often yield excellent ignition behavior but less favorable low-temperature flow than suitably branched isoparaffins. A finishing catalyst can improve cold-flow properties but may also promote hydrocracking and thereby decrease recovery of the desired middle-distillate fraction. Research on hydroisomerization and hydrogenation of renewable hydrocarbons clarifies the importance of selecting molecular branching and boiling-range targets appropriate to the end-use specification. A claim that the product is green diesel cannot substitute for a specified diesel qualification route and a measured property set.

Some articles discussing PFAD conversion have compared reactor-product properties against standards used for fatty acid methyl ester biodiesel. This is not equivalent to establishing conformance of a paraffinic hydrocarbon fuel. Researchers must identify whether the actual intended market involves automotive diesel blending, an HVO-type component, a neat paraffinic diesel or another refinery product and then apply the relevant property and testing requirements. The initial chemical family, distillation range, residual oxygen, cold-flow performance, stability and fuel-system compatibility must all be disclosed. The article thus treats product qualification as an independent evidence gate, not as an automatic consequence of high reactor yield.

Theme VI: Carbon Benefit Depends on Attribution, Alternative Uses and Actual Operation

The sixth theme concerns the difference between converting a renewable molecule and demonstrating climate benefit. PFAD is connected to oil-palm cultivation and commercial refining. Whether fuel receives substantial upstream emissions, and whether fuel production changes demand for palm oil or alternative PFAD uses, depends on how the product system is modeled. Xu et al. (2020) documented the sensitivity of PFAD renewable-diesel greenhouse-gas results to alternative attribution and land-use assumptions. This establishes a genuine methodological concern: treating PFAD as carrying no upstream burden can produce a favorable result that would not survive another defensible allocation model.

The same sensitivity appears in comparisons involving other lipid feedstocks, although exact figures are not transferable. Reviews of oilseed HEFA emissions, U.S. biodiesel and renewable diesel pathways, and recent biorefinery analyses show that energy supply, cultivation assumptions, product allocation and system boundaries strongly shape conclusions. A result based on attributional average inventory must not be presented as the same object as a consequential estimate incorporating displacement and market response. Transparent reporting of both approaches, when feasible, is preferable to allowing one selected classification to define the entire environmental claim.

PFAD refining and process-recycle arrangements further influence lifecycle outcomes. Studies of liquid biofuel from palm refining by-products compare once-through and recycle modes, while refinery integration and waste-derived renewable-diesel analyses illustrate sensitivity to process energy and plant configuration. Their findings support the need to evaluate realistic heat, hydrogen and electricity inputs for the PFAD route under consideration. They do not authorize transferring a published numerical carbon intensity to a refinery with a different hydrogen source, by-product accounting convention or co-processing fraction.

Economics has analogous boundary dependence. PFAD availability, competing purchasers, pretreatment intensity, catalyst replacement, hydrogen costs, feedstock logistics and product-credit mechanisms can alter project feasibility. Techno-economic studies of waste lipids and animal oils offer valuable cost categories, but nominal levelized costs from one region should not be portrayed as global prices. A commercially credible analysis should identify the incremental cost relative to a refinery's conventional operation and test alternative PFAD values and carbon-policy conditions.

This does not deny possible advantages of integration; it makes those advantages falsifiable rather than automatic.

Taken together, these six themes reject a single-metric notion of refinery readiness. A laboratory system may achieve substantial hydrocarbon formation while lacking demonstrated impurity tolerance or fuel conformity; a technically stable process may still have high hydrogen-related emissions; and a low-carbon scenario may depend on contestable PFAD classification. The results therefore motivate a multidimensional readiness architecture in which process and sustainability failures remain visible even when headline conversion improves.

Discussion and Analysis: The FCHRC Readiness Framework
Architecture of a Feedstock-Catalyst-Hydrogen-Refinery-Carbon framework

The critical synthesis supports the proposed Feedstock-Catalyst-Hydrogen-Refinery-Carbon (FCHRC) Readiness Framework. Its five domains are interdependent: verified feedstock quality, catalyst performance over useful time, net hydrogen and thermal requirements, refinery and fuel-product compatibility, and transparent lifecycle and market attribution. Each domain has its own evidence threshold and can invalidate a claim of industrial readiness even when another domain performs well. This is a conceptual evaluation framework, not a proprietary chemical catalyst, an optimized plant design or a system already demonstrated in commercial palm-oil refineries.

The feedstock domain specifies origin, analytical characterization, pretreatment, lot-to-lot variation and a defined supplier envelope. This domain determines whether results can be replicated outside a carefully chosen laboratory sample and supplies the physical basis for predicting poison accumulation. The catalyst domain then requires mechanistic interpretation of conversion and selectivity, continuous time-on-stream monitoring, spent-catalyst characterization and regeneration assessment. The two domains must be linked because a catalyst cannot be described as stable without specifying the feed in which stability was observed.

The hydrogen and thermal domain includes direct stoichiometric needs, hydrogenation of unsaturated species, sulfur-removal requirements of petroleum co-feeds, hydrogen recycle losses, gas separation, operating pressure and reactor exotherms. Process simulations must be constrained by independently verified mass and heat balances. The refinery-product domain then assesses fossil co-feed hydrotreating obligations, product fractionation, biogenic-carbon attribution, hydroisomerization and applicable finished-fuel requirements. A potential economic saving from using an existing reactor should be tested against additional catalyst exposure and utility demand, rather than counted as a guaranteed benefit of co-processing.

The carbon-governance domain sets a separate decision boundary: a renewable product designation is not itself a verified low-carbon conclusion. It requires reproducible system boundaries, transparent PFAD classification, alternative feedstock-use assumptions, hydrogen and energy scenarios, traceability, and comparison against relevant petroleum baselines. Importantly, an environmental assessment cannot repair a technically unsafe reactor, and technical efficiency cannot settle contested land-use or displacement effects. Accordingly, the framework uses explicit decision gates and independently inspectable indicators rather than combining all outcomes into a single unexplained score

Answering The Research Questions Through Evidence and Boundaries

RQ1 concerns the PFAD feed envelope. The review finds that free-fatty-acid concentration, acid composition, neutral oils, moisture and trace contaminants are relevant to both catalytic chemistry and equipment reliability. The appropriate output is a supplier- and catalyst-specific testing specification covering representative feed lots, not a claim that all PFAD streams are interchangeable. The proposed threshold should be tied to pretreatment capabilities, catalyst exposure and verified downstream product characteristics rather than to an arbitrary universal impurity limit.

RQ2 concerns reaction pathways and carbon economy. Hydrodeoxygenation can conserve carbon-chain length but consumes reducing equivalents, whereas decarboxylation and decarbonylation reduce the carbon number and generate carbon oxides. Ketonization, alcohol formation and wax ester formation complicate the simple three-pathway picture, especially under high acid activity. The primary research requirement is to close carbon, oxygen and hydrogen balances with measured gas and liquid products and to report carbon retained in the qualified fuel fraction rather than count all converted feed as equivalent finished product (Kim et al., 2024; Gamal et al., 2020; Zula et al., 2023). RQ3 addresses catalyst durability. Activity rankings cannot be generalized across feed compositions, conditions or catalyst age. Supported metals, phosphides, sulfides and acid-functional porous catalysts occupy different mechanistic design spaces, but a refinery needs reliable operation under the anticipated poisons, water activity, petroleum sulfur level and thermal load. Demonstrating fresh-catalyst hydrocarbon formation and showing retained selectivity after extended contaminated-feed testing should therefore be separate stages in experimental reporting. Multi-cycle reuse with filtered batch feeds is useful preliminary evidence but not equivalent to uninterrupted industrial catalyst life.

RQ4 separates dedicated conversion from true co-processing. Dedicated PFAD upgrading can demonstrate relevant oxygen-removal and finishing chemistry, while integrated co-hydroprocessing must meet original petroleum-stream desulfurization and product-quality duties concurrently. Studies using jatropha, used cooking oil or biocrudes provide transferable engineering mechanisms but do not prove PFAD performance in a particular petroleum unit. The missing validation is a matched comparison across fossil-only operation and increasing PFAD addition at controlled operating conditions, with catalyst-age and hydrogen effects measured prospectively.

RQ5 concerns hydrogen and finished fuels. Net hydrogen demand is a facility-level quantity influenced by chemistry, gas losses, hydrogen purity, recycle operation, sulfur removal and product finishing. Optimizing one conversion reaction while ignoring this balance can produce an apparent advantage that disappears in the full refinery system. Likewise, normal paraffin yield should not replace cold-flow, distillation and fuel-quality measurements. Reactor and hydrogen-network scenarios, accompanied by hydroisomerization trials when relevant, should define whether the resulting hydrocarbon fraction is commercially fit for its stated fuel application.

RQ6 asks whether low-carbon performance can be inferred from PFAD's industrial origin. It cannot. Attributional allocation, counterfactual PFAD demand, hydrogen sourcing and land-use response can materially alter lifecycle results, and existing literature documents this sensitivity. A credible environmental comparison should publish alternative assumptions and separate

emissions reductions attributable to chemical efficiency from reductions attributable to selected feedstock accounting conventions. Economic and carbon claims should also be tested against alternative PFAD uses and realistic market boundaries.

RQ7 concerns minimum proof of readiness. The synthesis identifies five independent evidence types: representative feed analysis, stable reactor and catalyst operation, full hydrogen and heat balances, finished-fuel and petroleum co-feed verification, and transparent carbon and economic assessment. None may be inferred merely from a favorable result in another. The framework consequently proposes stage-gated development in which failure at any domain leads to a narrower claim, re-engineering, further experiments or discontinuation rather than proceeding to larger facilities because a deadline or commercial target has been announced

A Multidimensional Evidence Scorecard for Refinery Qualification
The framework should be evaluated through separate criteria rather than an aggregate readiness percentage. Table 1 shows the key evidence domains, proposed indicators and required independent checks. The indicators are a methodological proposal, not a report of experimentally achieved thresholds. A useful scientific outcome can therefore be that one catalyst has attractive activity but insufficient durability evidence, or that one low-hydrogen route sacrifices too much liquid carbon for the intended use (Kim et al., 2024; Zhou et al., 2025; Arora et al., 2021).

The scorecard must also record the evidence class associated with every indicator. Laboratory PFAD conversion, related-feedstock pilot trials and measurements on catalysts exposed in an industrial hydrotreater provide different forms of support and should not be combined as if they document the same operating unit. Direct PFAD findings can inform pathway selection, adjacent industrial evidence can define test design, and proposed integration claims should remain hypotheses pending matched co-processing trials (Nur Azreena et al., 2024; Nejadmoghadam et al., 2025; Dimitriadis et al., 2024).

Table 1: Proposed Multidimensional Evidence Scorecard for PFAD Refinery Qualification

Readiness domain	Suggested measure	External verification / stop condition
PFAD/feed	FFA + neutral-oil spec; water; P, Na, K, Fe; lot variance	Measured representative lots; conditioning is practical
Reaction chemistry	Carbon and oxygen balances; hydrocarbon selectivity; H2 per qualified fuel	Measured liquid and gas outputs; no hidden oxygenate losses
Catalyst endurance	Continuous time on stream; poisons, coke, regeneration; product drift	Independent spent-catalyst diagnostics; useful durability
Refinery operation	Petroleum HDS baseline; temperature, quench, H2 recycle and pressure	Co-feed trial respects existing unit safety and sulfur limits
Fuel qualification	Boiling fractions, density, cold flow, cetane, residual oxygen	Relevant hydrocarbon-fuel standard; measured finished product
Carbon and economics	PFAD allocation cases; marginal hydrogen CI; alternative use; unit costs	Auditable assumptions; sensitivity does not negate claim

Source: Authorial conceptual synthesis based on the reviewed literature.

Table 1 emphasizes that apparent gains need independent verification across domains. Catalytic yield should be accompanied by carbon balances and clearly defined product categories; a durability study must document exposure time, material changes and relevant contaminants; and an integrated trial must preserve the petroleum unit's existing environmental and product obligations. Crucially, an analyst should not replace missing hydrogen-network data with reactor inlet pressure, nor present calculated low-carbon status without documenting PFAD classification and the displaced alternative use. Deficient evidence calls for a new experiment, not the assumption of a passing score.

Table 2 compares major oxygen-removal routes as qualitative design alternatives. The entries are mechanistic relationships under simplified conditions and should not be interpreted as measured PFAD yields. Real reactions can involve alkane cracking, double-bond saturation, intermediates, gas reactions and mixtures of routes. In particular, model acids differ from multicomponent PFAD and from PFAD blended with petroleum gas oil; measured atom balances are needed to establish the actual fraction taking each route .

Table 2: Qualitative Comparison of Competing Oxygen-Removal Pathways and Measurement Needs

Reaction route	Idealized carbon and hydrogen implications	Critical reporting question
Hydrodeoxygenation (HDO)	C16 acid to C16 alkane; oxygen as water; direct H2 required	Is net hydrogen plus fuel carbon retention measured?
Decarboxylation (DCO2)	C16 acid to C15 alkane and CO2; carbon shortened	Are liquid carbon loss and emitted/recovered CO2 reported?
Decarbonylation (DCO)	C16 acid to C15 alkane, CO and water; simplified H2 demand	Are CO, water-gas reactions and gas cleanup included?
Secondary chemistry	Hydrogenation, ketones, alcohols, wax esters, cracking	Are total oxygen, gas and hydrocarbon fraction closed?

Source: Authorial Conceptual Synthesis Based on the Reviewed Literature.

The comparison in Table 2 also explains why process optimization is multiobjective. A carbon-retaining HDO route may be attractive when renewable hydrogen is abundant, while a carbon-shortening route may reduce some direct hydrogen requirements but increase carbon gas emissions and change the distillation profile. Excess cracking can reduce desirable middle distillate in either case. Catalyst selection, heat release, hydroisomerization and refinery hydrogen requirements must therefore be assessed within one transparent system boundary rather than ranked by fuel yield measured on incompatible bases.

A Four-Gate Translational Roadmap with Independent Audit

Stage A defines feedstock and target chemistry. Candidate PFAD lots are identified from relevant supplier types; fatty-acid profiles, contaminants and competing uses are documented; and a reactor test is designed to distinguish HDO, decarbonylation, decarboxylation and secondary product formation. Experiments should compare the proposed catalyst with at least one relevant conventional baseline under matched conditions and report mass, carbon, oxygen and hydrogen balances. A proposed fuel stream cannot advance merely because its nominal conversion appears high while residual oxygen, product distribution or sample provenance remains unknown.

Stage B tests durability and operational sensitivity. The study moves from short batch screening to extended continuous operation using representative conditioned and less conditioned PFAD within predefined boundaries. Researchers measure conversion and selectivity over time, quantify the relevant poison content of feed and spent catalyst, and document regeneration where applicable. Hydrogen consumption and thermal behavior should be measured under realistic reactor severity. Independent characterization of active sites and deposits is needed before attributing any activity decline to one mechanism, while failure to meet durability or material-handling criteria requires redesign before escalation.

Stage C tests refinery integration rather than just chemical transformation. A pilot or demonstration unit compares the baseline petroleum stream with matched petroleum/PFAD co-feed runs, recording original desulfurization performance, bed temperature profiles, water and COx generation, hydrogen partial pressure, gas recycle and liquid fractionation. Finished-fuel properties and relevant upgrading requirements are measured in parallel. A sustainable operational claim should also include utility measurements, feed handling and the stability of performance under anticipated perturbations. Co-processing can proceed only when it preserves the refinery's primary specification and environmental constraints.

Stage D independently verifies carbon and business integrity before any larger scale claim. An external assessment examines fuel carbon origin, upstream PFAD classification, alternative PFAD markets, hydrogen source, process emissions, allocation and consequential scenarios, alongside catalyst costs, reliability and availability of feed. A fuel may be technically usable while failing the selected carbon-intensity requirement, or environmentally credible while economically inappropriate for a given refinery. Both outcomes should be reported without relabeling the product as universally successful. Figure 4 brings the four stages together through explicit go, redesign or stop conditions.

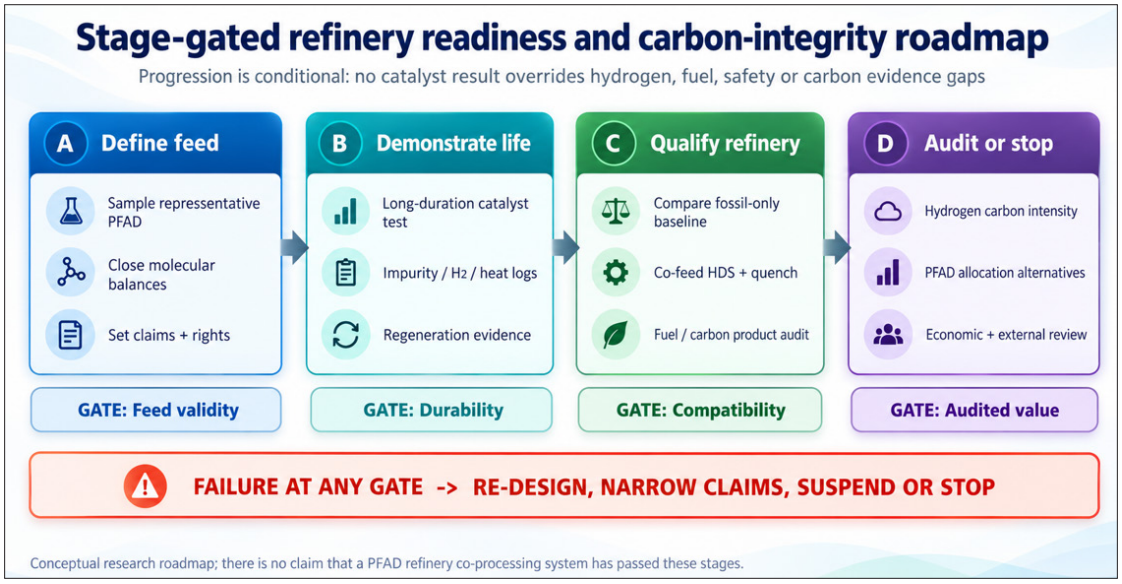


Figure 4: Stage-gated PFAD refinery-readiness roadmap with independent carbon and business audit. Source: Authorial conceptual synthesis; no measured field performance is implied.

Figure 4 uses gates to protect the interpretation of evidence rather than to delay innovation unnecessarily. The first gate concerns a defensible target and a measured feed; the second concerns conversion and durability under relevant conditions; the third concerns integrated operation and qualified outputs; and the fourth concerns auditable environmental and economic outcomes. A failed gate can still produce valuable scientific results, including knowledge that a particular pathway should remain dedicated rather than co-processed. The stopping rule prevents investment decisions from relying on a single favorable laboratory metric.

Implications for Refinery Managers, Researchers and Public Policy

Refinery managers should prioritize a narrow business case instead of a generic announcement that PFAD can replace fossil diesel. This means specifying the intended refinery unit, petroleum co-feed, target PFAD supplier base, hydrogen network, operating envelope and required fuel product. Procurement agreements should identify actionable quality characteristics, while plant trials should report catalyst condition and utility burdens. The result is an evidence-based decision regarding where PFAD is an appropriate additive or dedicated feedstock, rather than a promotional feedstock-neutral green diesel claim.

Catalyst developers should design studies around industrial failure modes as carefully as they design studies around high selectivity. Particularly informative experiments will expose catalysts to controlled phosphorus, alkali, water and relevant petroleum sulfur within justified safety procedures, measure time-on-stream, and identify changes in the surface and product distribution. Advanced MOF-derived or zeolite-supported catalysts may be promising, but their potential should be compared with commercially meaningful baselines and well-characterized feeds. Negative results from poisoning, fouling or unfavorable mixed-feed interactions should be reported because they narrow the uncertainty that refinery engineers must manage.

Researchers investigating hydrogen and downstream processing should distinguish product selectivity at one catalytic stage from net facility demand. Reaction-pathway maps, reactor heat-balance calculations, gas analyses and product fractionation should be incorporated early, not added after reporting a peak liquid yield. Comparative studies should also examine whether hydroisomerization is necessary to meet cold-flow expectations and whether its additional hydrogen demand and cracking penalties change the original preferred pathway. Transparent comparisons of isolated and integrated operation could make the literature more useful to both petroleum and renewable-fuel specialists.

Public authorities and sustainability certifiers should separate support for research into renewable feedstocks from certification of achieved emissions reductions. PFAD traceability and classification require special attention because a market-valued palm-oil refining stream may displace existing uses. Emissions assessment should disclose allocation choices, indirect effects, hydrogen supply and uncertainty intervals, preferably including alternative scenarios. Rules that reward a material solely because it is called waste risk misrepresenting actual marginal consequences; rules that prohibit investigation without considering improved processes may miss useful industrial opportunities. A more defensible approach combines verifiable sourcing, comparable carbon methodology and independent technical qualification.

Research Limitations and Future Validation

Several boundaries limit what the review can conclude. This is a purposive qualitative synthesis rather than an exhaustive search, and the selected studies differ in reactor type, feed chemistry, catalyst condition, performance denominator and reporting completeness. Much of the mechanistic literature involves isolated fatty acids or non-PFAD materials; evidence from these studies is appropriate for formulating hypotheses but cannot replace direct PFAD co-feed experiments. Moreover, industrial operating data on catalyst replacement, desulfurization interactions and real feed impurities may be commercially inaccessible. These limitations preclude a universal blend fraction, technology winner, hydrogen-intensity estimate or certified lifecycle saving.

The next scientific advances would come from independently replicable comparative experiments. They should use standardized, analytically characterized PFAD lots; document continuous operation and catalyst aging; test meaningful co-feed perturbations; and report qualified hydrocarbon fractions together with product-carbon balance, hydrogen intensity and upstream allocation assumptions. Where a refinery-specific comparison cannot yet be conducted, studies should label their results as proof of reaction chemistry or process simulation rather than demonstration of deployment. The FCHRC framework is intended to make those distinctions explicit and to provide a falsifiable route from research to qualification [1-57].

Conclusion

Palm fatty acid distillate presents a technically credible source of long-chain fatty acids for producing diesel-range hydrocarbons, and research across supported metal catalysts, sulfides, phosphides and emerging porous materials has established several feasible conversion pathways. However, demonstrating molecular conversion under controlled conditions is fundamentally different from qualifying PFAD for continuous processing with petroleum distillates. The principal conclusion of this qualitative review is that refinery readiness requires a linked assessment of feedstock quality, reaction selectivity, catalyst durability, refinery hydrogen and thermal capacity, finished-product conformity, and lifecycle carbon attribution. None of those requirements is automatically fulfilled by favorable conversion, yield or product-boiling-range data.

The synthesis identifies six related challenges: variable PFAD composition and adsorption effects; trade-offs between carbon retention and hydrogen requirements; insufficient industrially representative catalyst-aging evidence; interactions between biogenic oxygen removal and existing petroleum processing obligations; hydrogen-system and product-finishing constraints; and sensitivity of greenhouse-gas claims to feedstock classification and counterfactual use. These themes imply that a general preference for hydrodeoxygenation, decarboxylation, or any single catalyst family would be premature. The appropriate process configuration depends on the intended refinery and feed supply, the source and cost of hydrogen, the target fuel specification, and the independently verified environmental boundary.

The proposed Feedstock-Catalyst-Hydrogen-Refinery-Carbon Readiness Framework provides an integrated conceptual route for making those decisions transparent. It recommends representative feed characterization; stoichiometrically explicit oxygen, hydrogen and carbon balances; extended fixed-bed and regeneration testing; controlled trials with real petroleum co-feeds; verification of fuel properties and biogenic-carbon recovery; and multiple lifecycle scenarios that disclose feedstock allocation, displacement and land-use assumptions. A stage-gated program should allow redesign, narrowed claims or termination whenever these requirements are not met. The purpose is not to obstruct renewable-fuel innovation but to ensure that more ambitious claims are supported by correspondingly stronger evidence.

For industrial practitioners, the immediate recommendation is to define one refinery-specific, testable use case before selecting a catalyst or announcing a renewable replacement target. For researchers, the priority is interoperable reporting of conversion pathways, durability and complete process balances, including

negative or mixed results. For policymakers and certifiers, the priority is transparent accounting of PFAD's economic and environmental status rather than automatic classification as a carbon-free waste. Future research should compare long-duration PFAD co-processing across different petroleum feedstocks and hydrogen sources while incorporating product-finishing, market displacement and consequential environmental effects. Until that evidence becomes available, PFAD conversion can reasonably be called promising, but an unqualified claim of refinery-wide readiness or universally low-carbon production remains scientifically unsupported.

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