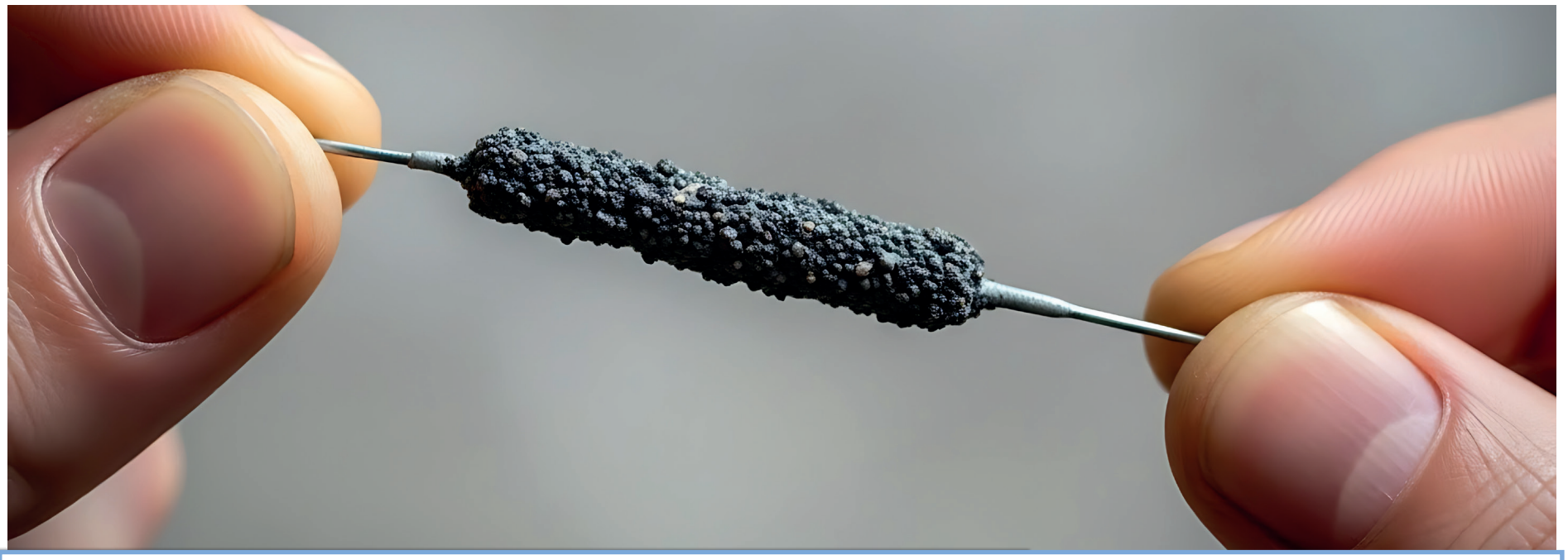

ADVANCED CATALYST DEVELOPMENT: INNOVATIONS IN CRUDE OIL PROCESSING, CLEANER FUELS, AND PETROCHEMICAL PRODUCTION

Abstract

Converging pressures from tightening emissions regulations, heavier crude feedstocks, and the petrochemical industry's rising claim on global oil demand have created an urgent need for catalytic systems that outperform their predecessors on multiple fronts. This paper reviews three categories of recent catalyst innovation: dispersed nanocatalysts for heavy crude hydrocracking, bifunctional zeolite frameworks for direct oil-to-chemicals conversion, and green lifecycle strategies for spent catalyst management. Quasi-single-layer molybdenum disulfide formulations have achieved liquid product yields above 96 wt%, while trimetallic dispersions raised middle distillate output by 52%. Modified ZSM-5 zeolites now reach olefin selectivities as high as 69%, and the 7 billion USD S-Oil Shaheen project is poised to validate direct crude-to-chemicals conversion at industrial scale. Earth-abundant tungsten carbide has been shown to outperform platinum tenfold in polyolefin hydrocracking, and chelant-assisted hydrometallurgy recovers over 95% of valuable metals from deactivated catalysts. Taken together, these advances suggest a coherent pathway toward a refining paradigm that is more efficient, more profitable, and less environmentally damaging. Facilities that adopt these catalytic systems are better positioned to remain profitable as crude quality declines and the global product mix shifts from fuels toward chemicals.

Introduction

Petroleum refining is one of the few sectors of the chemical industry that face many simultaneous constraints. Global refining capacity stands at roughly 103.5 million barrels per day, yet feedstocks have been trending heavier, more sulfurous, and more metalliferous for years [1]. The International Maritime Organization's 2020 sulfur cap cut allowable marine fuel sulfur from 3.5% to 0.5%, displacing an estimated 3.7 million barrels per day of high-sulfur fuel oil [2]. In the United States, the EPA Tier 3 standard limits gasoline sulfur to 10 ppm [3]. Europe's forthcoming Euro 7 regulation, effective November 2026 for new light-duty vehicles, extends mandatory catalyst durability from 100,000 to 200,000 kilometers and requires a 35% reduction in nitrogen oxide emissions [4, 5]. Meeting all of these mandates simultaneously, on deteriorating feedstock quality, demands a new generation of catalytic materials.

Compounding these regulatory pressures is a structural shift in what refineries are expected to produce. As transport electrification erodes long-term fuel demand, the petrochemical sector has emerged as what the IEA calls the primary source of oil demand growth from 2026 onward, with projected consumption reaching 18.4 million barrels per day by 2030 [1]. Conventional refining converts only 8% to 12% of a barrel into chemicals; emerging oil-to-chemicals pathways target 60% to 80% [6]. The global refinery catalyst market, valued between 5.4 and 8.3 billion USD in 2023 to 2024, is projected to reach 7.1 to 14.3 billion USD by the early 2030s at a compound annual growth rate of roughly 3.1% to 4.4% [7, 8]. This paper focuses on three catalyst innovation fronts that respond most directly to these converging pressures: nanocatalysts that make deteriorating feedstocks processable, bifunctional zeolites that enable the product-slate shift toward chemicals, and green lifecycle strategies that address the growing environmental burden of catalyst waste itself.

Nanocatalysts for Heavy Crude Hydrocracking

Heavy crude upgrading remains so challenging largely because of asphaltenes. These polyaromatic nanoaggregates, with molecular weights typically between 500 and 1000 g/mol, are too bulky to penetrate the mesoporous networks of conventional alumina-supported catalysts, leading to pore plugging and rapid deactivation [9]. Slurry-phase hydrocracking offers an alternative: by dispersing catalytic nanoparticles directly within the heavy oil, active sites encounter asphaltene aggregates in suspension, largely sidestepping the diffusion bottleneck.

The most striking results involve morphologically engineered molybdenum disulfide. Zheng et al. at the Dalian Institute of Chemical Physics synthesized quasi-single-layer MoS2 via a solvothermal route using L-cysteine as a sulfur precursor and ethylene glycol as the solvent. Because MoS2 basal planes are largely inert while edge and rim sites drive hydrogen activation, keeping the material to a single layer is critical. In the hydrogenation of anthracene, a model polyaromatic compound, this catalyst achieved 83.1% selectivity toward octahydroanthracene, an 11.4-fold improvement over bulk MoS2, with 54.0% total hydrogenation [10].

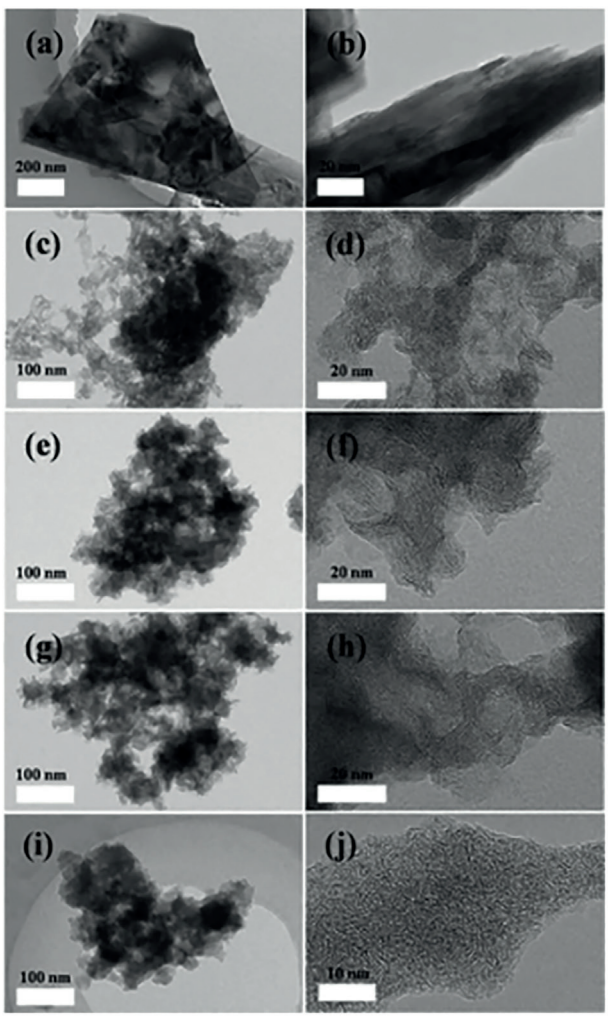

Figure 1. TEM and HRTEM images of MoS2 catalysts prepared under varying synthesis conditions. Low-magnification TEM images (left column) and corresponding HRTEM images (right column) are shown for (a, b) commercial bulk MoS2, (c, d) hydrothermally synthesized MoS2 using thioacetamide as the sulfur precursor (HT-TAA), (e, f) hydrothermally synthesized MoS2 using glutathione (HT-GSH), (g, h) hydrothermally synthesized MoS2 using L-cysteine (HT-LC), and (i, j) solvothermally synthesized MoS2 using L-cysteine in ethylene glycol (ST-LC) [10].

Figure 1 shows TEM and HRTEM images of MoS2 catalysts synthesized under these varying conditions, illustrating the progressive reduction in slab thickness and particle size from commercial bulk MoS2 to the solvothermally synthesized quasi-single-layer material. The morphological progression visible across the five catalyst preparations is directly tied to catalytic performance. Commercial bulk MoS2, panels (a) and (b), exhibits

thick, heavily stacked slabs with minimal edge-site exposure, which accounts for its low hydrogenation activity. As synthesis conditions shift toward the solvothermal route using L-cysteine in ethylene glycol, panels (i) and (j), the resulting particles become predominantly single-layer with slab lengths below 10 nm, maximizing the fraction of catalytically active edge and rim sites relative to inert basal planes. It is this structural difference that underlies the 11.4-fold selectivity improvement reported by Zheng et al. [10].

Work at China's State Key Laboratory of Heavy Oil Processing pursued a different precursor, generating presulfided MoS2 nanoparticles with slab lengths of 5 to 11 nm and 1 to 2 stacking layers. At 410 degrees Celsius and 8.0 MPa hydrogen pressure, these particles boosted liquid yield to 96.4 wt% while collapsing coke formation from 14.05% to 0.19 wt%, a 98.6% reduction. By comparison, conventional oil-soluble catalysts processing vacuum residue in slurry-phase autoclaves have typically achieved total distillate yields of over 70% [9]. A liquid recovery approaching 96 wt%, if validated at scale, would represent a substantial gain in saleable product per barrel, while coke yields below 0.2 wt% would significantly reduce equipment fouling costs and unplanned shutdown frequency.

Monometallic systems do not exhaust the design space, however. Rawat et al. tested a presulfided trimetallic nickel-cobalt-molybdenum formulation on Bombay High crude oil and reported that middle distillate yield rose from 34.75 to 52.92 wt%, a 52% relative increase, with solid coke formation eliminated entirely [11]. Deep desulfurization kinetics have benefited from similar structural optimization. A Ni-MoS2 catalyst from the SINOPEC Research Institute, with slab dimensions of 20 to 36 nm lateral size and 5.4 stacking layers, achieved 94.7% desulfurization of dibenzothiophene at only 320 degrees Celsius, well below conventional hydrotreating temperatures [12]. Slurry-phase operation introduces additional challenges beyond feedstock access, however. Unsupported nanoparticles are subject to thermal agglomeration, progressive carbonaceous deposition, and difficult post-reaction separation from liquid products, all of which have historically limited the commercial viability of dispersed catalyst systems. Longevity data from Wang et al. suggest that some of these concerns may be manageable: slurry-phase MoS2 retained 92.0% of initial activity after 12 continuous reaction cycles, roughly 1.7 times the residual activity observed in gas-phase-aged equivalents [13]. Several patterns emerge from Table 1. First, the performance gap between monometallic and multimetallic systems is substantial. The quasi-single-layer MoS2 excels at selective hydrogenation of model polyaromatic compounds, but the trimetallic Ni-Co-Mo formulation achieves broader feedstock-level improvements, raising middle distillate yield by over 50% on actual crude oil. Second, the data suggest that nanoscale morphology control and compositional tuning address different bottlenecks: slab geometry governs edge-site exposure and therefore intrinsic hydrogenation activity, while metal promotion lowers the activation barrier for hydrogen dissociation across the entire catalyst surface. Third, the Wang et al. longevity result, 92% activity retention after 12 cycles, is notable because it begins to address the concern that unsupported nanoparticles would degrade too rapidly for practical use. Taken together, these results indicate that no single catalyst architecture optimizes all performance dimensions simultaneously, and that refinery operators may need to match catalyst design to specific feedstock and product requirements.

Table 1

Performance Metrics of Advanced Nanocatalysts in Heavy Oil Upgrading [9, 10, 11, 12, 13]

Catalyst Type	Active Metals	Key Performance Metric
Quasi-Single-Layer	MoS2	83.1% selectivity to octahydroanthracene
Presulfided Dispersed	MoS2	96.4 wt% liquid yield, 0.19 wt% coke
Trimetallic Dispersed	Ni-Co-Mo	Middle distillate yield: 52.92 wt%
Optimized Bimetallic	Ni-MoS2	94.7% desulfurization at 320 C
Slurry-Phase Aged	MoS2	92.0% activity retained after 12 cycles

Oil-to-Chemicals Zeolite Catalysts

If the nanocatalyst literature addresses how to process heavier or more challenging feedstocks, the oil-to-chemicals literature addresses a different question: how to make different products. Traditional FCC was optimized for gasoline and middle distillates. The new imperative is to maximize yields of light olefins, principally ethylene, propylene, and butylenes, which serve as feedstocks for plastics, fibers, and commodity chemicals. Zeolite ZSM-5 has long been used as an FCC additive, but unmodified ZSM-5 is poorly suited to this task. Bimolecular hydrogen transfer reactions consume desired olefins and produce unreactive paraffins, competing directly with the monomolecular cracking pathway that generates the olefins. The research reviewed below represents a set of strategies for shifting this competition.

One strategy involves physical passivation of external acid sites. Al-Shafei et al. [14] encapsulated ZSM-5 within a 24-nm amorphous silica shell, restricting non-selective bimolecular reactions while pore constraints in the interior favor monomolecular cracking. Steaming generated additional mesopores and reduced acidity. Under optimized steam co-feeding, olefin selectivity jumped from 23.8% to 69.0% [14]. Chemical doping offers a different lever. Jermy et al. demonstrated that impregnating 2 wt% manganese onto ZSM-5 synthesized from halloysite, a template-free route, produced 47 wt% light olefins from Arab Extra Light crude at 675 degrees Celsius, with 22% ethylene and 18% propylene yields [15]. Calcium-doped ZSM-5 from Wuhan University achieved 43.34 wt% light olefins with 78% C2-C4 selectivity in the methanol-to-olefin process, suggesting the framework's tunability extends across different feedstock chemistries [16].

These modifications are not without tradeoffs, however. Reducing acid site density to favor monomolecular cracking generally improves olefin selectivity, but it also suppresses total feedstock conversion. Ali et al.'s P/La-modified catalyst achieved 62% olefin selectivity, for instance, but only at 77% n-hexane conversion, meaning nearly a quarter of the feed passed through unreacted [17]. Similarly, the core-shell silica approach reduced total acidity by roughly 75% after steaming, which suppressed coke and dry gas formation but also lowered overall gas oil conversion relative to the unmodified parent zeolite [14]. Catalyst designers must therefore balance selectivity against per-pass conversion, recognizing that higher olefin purity may come at the cost of requiring recycle loops or larger reactor volumes.

More complex dopant combinations allow finer control. Ali et al. studied n-hexane cracking, a model light alkane, over ZSM-5 modified with 1 wt% phosphorus and 0.25 wt% lanthanum. Lanthanum stabilized the framework against dealumination, while phosphorus neutralized strong Bronsted sites to generate weaker Lewis acid sites. The resulting catalyst achieved 62% light olefin selectivity at 77% conversion, with BTX byproducts suppressed to 3% [17]. At larger scale, the ACM-101 catalyst developed by Alabdullah et al. at KAUST and Saudi Aramco incorporates silicon carbide for superior heat transport. Processing untreated Arabian Light crude in a multi-zone fluidized bed, ACM-101 sustained single-pass olefin yields above 30 wt% [18].

The choice of a multi-zone fluidized bed rather than a conventional fixed-bed reactor is itself significant. Catalytic cracking of whole crude oil is highly endothermic, and fixed-bed reactors struggle to distribute heat uniformly across the catalyst bed, creating localized cold spots that reduce conversion and hot spots that accelerate coking and degrade selectivity. The ACM-101 system addresses this by incorporating silicon carbide, which has thermal conductivity roughly ten times higher than alumina, directly into the catalyst particle. The fluidized bed configuration further improves heat distribution by maintaining continuous catalyst circulation between the reaction zone and a regeneration zone where coke is combusted to supply process heat [18]. This integrated thermal management is difficult to replicate in fixed-bed systems, which may limit the transferability of these results to existing refinery infrastructure without substantial capital investment.

Whether these laboratory results can translate commercially is no longer speculative. The S-Oil Shaheen project in Ulsan, South Korea, a 7 billion USD investment backed by Saudi Aramco, represents the first commercial deployment of Thermal Crude-to-Chemicals (TC2C) technology. As of early 2026, the project had surpassed 92% overall completion, with mechanical completion targeted for June 2026 and commercial operations expected in the second half of the year [19, 20, 31]. The plant is expected to convert over 65% of feed crude directly into chemicals, yielding 1.8 million tonnes of ethylene and 770,000 tonnes of propylene annually [19, 20].

Whether the Shaheen project will prove competitive against conventional refining depends heavily on the petrochemical price cycle. At current ethylene and propylene margins, the facility's ability to convert over 65% of feed crude to chemicals rather than the 8% to 12% typical of conventional refineries suggests a favorable revenue mix. However, the project carries concentration risk: a 7 billion USD facility optimized for chemical output is less flexible than a traditional refinery that can shift between gasoline, diesel, and jet fuel depending on market conditions. If petrochemical overcapacity, particularly from Chinese ethylene expansion that added over 33 million tonnes of new capacity between 2014 and 2024, depresses margins during the project's early operating years, the return on investment could be delayed [20].

Saudi Aramco's broader portfolio includes the CC2C catalytic route developed with Axens, targeting over 60% conversion, and a planned Aramco/SABIC complex to process 400,000 barrels per day into 9 million tonnes of chemicals at an estimated 20 billion USD [21]. Sinopec's Deep Catalytic Cracking process already achieves over 24% propylene yield and more than 40% combined C2-C4 olefin yield from heavy distillates using MFI zeolite catalysts [22].

Table 2 reveals that ZSM-5 modification strategies differ not only in the magnitude of olefin selectivity improvement but in the mechanism by which they achieve it. The core-shell SiO2 approach, which nearly tripled selectivity from 23.8% to 69.0%, operates through physical passivation of external acid sites rather than chemical alteration of the framework itself. By contrast, the P/La dual-dopant strategy achieves a comparable selectivity of 62% by restructuring the acid site distribution at the atomic level, converting strong Bronsted sites into weaker Lewis sites. It is also worth noting that these results were obtained on different feedstocks and under different conditions: the core-shell data derive from heavy atmospheric gas oil cracking, the Mn-modified data from Arab Extra Light crude, and the P/La data from n-hexane, a model compound. Direct numerical comparison across rows should therefore be made cautiously. What the table does demonstrate collectively is that multiple independent research groups, working with different feedstocks and modification strategies, are converging on olefin selectivities in the 47% to 69% range, well above the levels achievable with unmodified ZSM-5. Figure 2 summarizes the olefin selectivity gains across these four modification strategies, illustrating the range of improvement relative to unmodified ZSM-5.

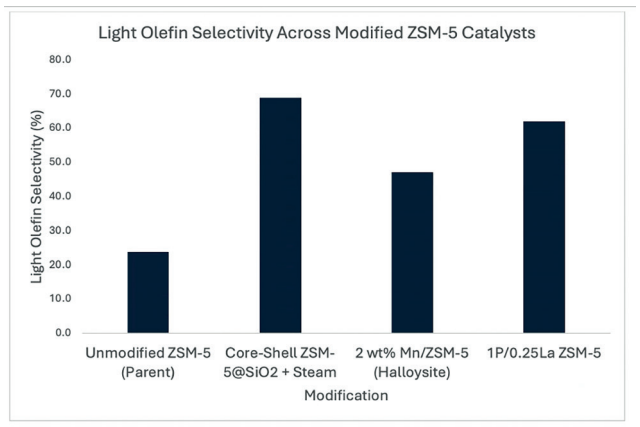

Figure 2. Light olefin selectivity across modified ZSM-5 catalysts. Unmodified ZSM-5 (Parent) represents baseline performance without steam co-feeding at 600 degrees Celsius [14]. Core-Shell ZSM-5@SiO2 + Steam reflects performance at a water/oil ratio of 2:1 at 600 degrees Celsius [14]. 2 wt% Mn/ZSM-5 (Halloysite) was tested on Arab Extra Light crude at 675 degrees Celsius [15]. 1P/0.25La ZSM-5 was tested on n-hexane at elevated temperature [17].

Table 2

ZSM-5 Modifications for Oil-to-Chemicals Conversion [14, 15, 17, 18]

Modification	Structural Function	Light Olefin Metric
Core-Shell SiO2	Passivates external acid sites	Selectivity: 23.8% to 69.0%
2 wt% Mn	Alters acid site density	47 wt% olefins from crude
1P/0.25La	Framework stabilization, Lewis acidity	62% selectivity (n-hexane); BTX to 3%
SiC (ACM-101)	Thermal management	>30 wt% from raw Arabian Light

Green Catalysts and Lifecycle Management

The conversation about catalyst innovation cannot end at the reactor outlet. Petroleum refining generates over 270,000 tonnes of spent hydroprocessing catalyst each year, material that is classified as hazardous waste under U.S. EPA RCRA listings K171 and K172 because of its heavy metal content [23]. The volumes are growing at roughly 5% annually. Two broad responses have emerged: recovering the metals locked inside deactivated catalysts, and designing new catalysts from cheaper, more abundant elements in the first place.

Metal Recovery from Spent Catalysts

On the recovery front, chelant-assisted hydrometallurgy has proven effective. Marafi and Rana showed that ultrasonic-assisted leaching with 10 wt% EDTA at 60 degrees Celsius over 6 hours could extract 97.0% of molybdenum, 95.0% of nickel, and 94.0% of vanadium from spent catalysts. Up to 95.0% of the EDTA itself is recoverable through pH-adjusted precipitation, enabling closed-loop operation [24]. Refiners adopting such programs report cost savings of 45% to 50% relative to virgin catalyst procurement, and approximately 68% of major refineries now practice some form of regeneration. BASF's Environmental Catalyst and Metal Solutions division reports that recycling platinum-group metals produces 97% less CO_2 than primary mining [25]. The catalyst regeneration market, valued at 3.66 billion USD in 2024, is projected to reach 12.48 billion USD by 2032 [7].

Earth-Abundant Catalyst Alternatives

Replacing precious metals altogether may prove even more consequential. Research published in the Journal of the American Chemical Society demonstrated that nanoscale tungsten carbide functions as an intrinsically bifunctional catalyst for polyolefin hydrocracking, with metallic tungsten phases providing hydrogenation activity and surface hydroxyl groups serving as Bronsted acid sites. On a per-acid-site basis, this formulation performed more than ten times more efficiently than platinum-based counterparts, maintaining elevated activity even when plastic feedstock contained 10 wt% polyvinyl chloride, a contaminant that irreversibly poisons `noble metals [26]. The economic and environmental advantages of this substitution are substantial. Earth-abundant transition metals used in such catalysts trade at a fraction of palladium's price, which exceeds 30,000 USD per kilogram, and their production generates roughly 600 times less CO_2 per kilogram [27, 28]. Table 3 presents a comparative analysis of material costs and CO_2 emissions intensity for earth-abundant versus noble metal catalyst precursors, illustrating the scale of the economic and environmental gap between these two classes of materials.

Table 3

Tungsten Carbide versus Noble Metal Catalysts for Polyolefin Hydrocracking [26, 27, 28]

Property	Earth-Abundant (Ni, W)	Noble Metals (Pt, Pd)
Per-BAS hydrocracking rate	>10x higher than Pt baseline	Baseline (1x)
PVC tolerance (10 wt%)	Activity maintained or increased	Activity dropped >70%
Material cost	<$16/kg (Ni)	>$30,000/kg (Pd)
CO_2 per kg produced	~600x lower than noble metals	Baseline (high)

If tungsten carbide outperforms platinum on both cost and activity, the question arises why platinum remains the industry standard. The answer lies largely in maturity and infrastructure. Platinum-based hydrocracking catalysts have decades of commercial operating history, well-established regeneration protocols, and predictable deactivation kinetics that refiners can model with confidence. Tungsten carbide, by contrast, was first demonstrated for polyolefin hydrocracking only in late 2025, and critical questions about long-term stability, optimal regeneration procedures, and behavior across diverse feedstock compositions have not yet been answered at commercial scale. Industrial adoption of new catalyst chemistries typically lags laboratory discovery by 5 to 15 years, as pilot testing, process engineering, and regulatory qualification proceed incrementally.

Biodesulfurization

Biological catalysis offers a different approach. The Rhodococcus erythropolis XP strain removed 94.5% of organic sulfur from diesel oil at just 30 degrees Celsius and atmospheric pressure via the 4S metabolic pathway, which cleaves sulfur from heterocyclic rings without breaking carbon-carbon bonds [29]. In a refinery process flow, biodesulfurization would most likely be positioned downstream of the conventional hydrotreating unit, operating as a polishing step on partially desulfurized product streams. The hydrotreater removes the bulk of sulfur compounds that are kinetically accessible at high temperature and pressure, while the biodesulfurization unit would target the sterically hindered dibenzothiophene derivatives that resist conventional catalytic treatment, the so-called last 50 ppm problem that makes the difference between a compliant and non-compliant fuel. Genetic refactoring of the dsz operon in an engineered DRB strain pushed performance further, achieving 96.0% dibenzothiophene conversion in 3 hours at a specific rate of 120 micromoles per gram dry cell weight per hour [30].

The recovery efficiencies in Table 4 are consistently above 94% for all three target metals, with molybdenum reaching 97%. Two aspects of these results merit attention. First, the conditions under which these rates are achieved, 60 degrees Celsius and atmospheric pressure with ultrasonic agitation, are considerably milder than pyrometallurgical alternatives, which typically require temperatures above 1000 degrees Celsius. This translates into lower energy costs and reduced secondary emissions. Second, the 95% recoverability of the EDTA chelant itself is what makes the process economically viable as a closed-loop system rather than a single-use extraction. Without solvent recycling, the cost of EDTA consumption would offset much of the value recovered from the metals.

> *Converging pressures from tightening emissions regulations, heavier crude feedstocks, and the petrochemical industry's rising claim on global oil demand have created an urgent need for catalytic systems that outperform their predecessors on multiple fronts.*

Comparing these three approaches, metal recovery via EDTA chelation is the most commercially mature, already adopted by roughly 68% of refineries, and offers immediate cost savings without requiring changes to reactor design. Tungsten carbide catalysts are the most scientifically promising in terms of performance but remain at the laboratory stage with no commercial deployment reported to date. Biodesulfurization occupies a middle ground: the underlying biochemistry is well characterized, but the engineering challenges of scaling biphasic reactors to refinery volumes have yet to be solved. In the near term, chelant-based recovery and noble metal substitution are likely to develop along parallel tracks, with biodesulfurization serving as a longer-horizon complement rather than a replacement for conventional hydrodesulfurization.

Table 4

EDTA-Assisted Metal Recovery from Spent Hydroprocessing Catalysts [24]

Metal	Agent	Conditions	Recovery	Source
Molybdenum	10 wt% EDTA	60 C, 6 hr, ultrasonic	97.0%	Marafi & Rana [24]
Nickel	10 wt% EDTA	60 C, 6 hr, ultrasonic	95.0%	Marafi & Rana [24]
Vanadium	10 wt% EDTA	60 C, 6 hr, ultrasonic	94.0%	Marafi & Rana [24]
EDTA Solvent	pH Adjustment	Dechelation/ precipitation	95.0%	Marafi & Rana [24]

Conclusion

The three research fronts reviewed here, nanoscale hydrocracking catalysts, bifunctional OTC zeolites, and green lifecycle strategies, address different bottlenecks but share a common logic: squeezing more value from each barrel of crude while generating less waste and consuming less energy. Dispersed MoS2 nanocatalysts now deliver liquid yields above 96 wt% and near-total asphaltene conversion, making heavy and unconventional crudes viable feedstocks for the first time at scale. Modified ZSM-5 frameworks reach olefin selectivities as high as 69%, and the imminent commissioning of the 7 billion USD S-Oil Shaheen project will test whether these laboratory selectivities hold under continuous commercial operation. Meanwhile, tungsten carbide's tenfold efficiency advantage over platinum in polyolefin hydrocracking, combined with EDTA-based metal recovery rates above 95%, offers a plausible blueprint for closing the loop on catalyst lifecycle costs and toxic waste generation.

Open questions remain. The long-term stability of unsupported nanocatalysts in continuous industrial slurry loops has not been fully demonstrated beyond pilot scale. Biodesulfurization, despite strong kinetics in controlled settings, still faces mass-transfer constraints at commercial volumes. And the extent to which OTC conversion will actually displace conventional fuels refining depends on macroeconomic variables that no catalyst can control. What the literature does make clear is that the catalytic toolbox available to the refining industry has expanded considerably since 2021, and that the convergence of nanoscale engineering, zeolite architecture, and circular lifecycle thinking is producing solutions that are not merely incremental but qualitatively new.

Of the three innovation fronts reviewed, oil-to-chemicals zeolite technology is the most likely to reach commercial scale first, and in fact is already doing so through the S-Oil Shaheen project. The underlying FCC and steam cracking infrastructure is well understood, and the modifications required, principally zeolite reformulation and reactor reconfiguration, build on decades of industrial experience rather than requiring entirely new process paradigms. Nanocatalyst-based slurry hydrocracking, while technically impressive, faces a longer path to adoption because it demands reactor architectures and catalyst recovery systems that most existing refineries do not possess. Green lifecycle strategies, particularly EDTA-based metal recovery, are already widely implemented but represent incremental cost savings rather than transformative capacity additions. In terms of economic impact, the oil-to-chemicals transition is likely the most consequential. A single facility like Shaheen, by redirecting over 65% of crude throughput from fuels to chemicals, can generate revenue per barrel that is several times higher than conventional fuel refining, provided petrochemical margins remain favorable. This product-slate shift, replicated across the dozens of OTC projects currently in various stages of planning globally, has the potential to reshape the economics of the entire downstream petroleum sector.

Works Cited

[1] Executive summary, Oil 2025, Analysis. International Energy Agency, 2025. https://www.iea.org/reports/oil-2025/executive-summary

[2] "The Effects of Changes to Marine Fuel Sulfur Limits in 2020 on Energy Markets." U.S. Energy Information Administration, Mar. 2019.

[3] "Emission Standards: USA: Cars and Light-Duty Trucks, Tier 3." DieselNet, dieselnet.com/standards/us/ld_t3.php.

[4] L. Mendez, "What You Need to Know About the Euro 7 Emissions Standards." Blackcircles, Mar. 2026.

[5] A. Woodhouse and N. Jain, "What is Euro 7 emissions standard?" Autotrader, 2024.

[6] H. Khan, "Crude Oil-to-Chemicals: Future of Refinery." FutureBridge, Dec. 2019.

[7] "Refinery Catalyst Market Size, Share & Growth Report, 2030." Grand View Research.

[8] N. Kaitwade, "Refinery Catalyst Market Growth, Trends & Forecast 2025 to 2035." Future Market Insights, May 2025.

[9] B. Liu et al., "Slurry phase hydrocracking of vacuum residue in the presence of presulfided oil-soluble MoS2 catalyst," Fuel, vol. 246, pp. 133-140, Jun. 2019.

[10] A. Zheng et al., "Highly Efficient MoS2 Nanocatalysts for Slurry-Phase Hydrogenation of Unconventional Feedstocks into Fuels," Energy & Fuels, vol. 35, no. 3, pp. 2590-2601, Jan. 2021.

[11] A. Rawat et al., "Direct slurry-phase hydrocracking of crude

oil using trimetallic nanocatalyst," Fuel, vol. 330, p. 125448, Dec. 2022.

[12] C. Yang et al., "Study on the Performance of Ni-MoS2 Catalysts with Different MoS2 Structures for Dibenzothiophene Hydrodesulfurization," ACS Omega, vol. 8, no. 44, pp. 41182-41193, Oct. 2023.

[13] D. Wang et al., "Stability of MoS2 Nanocatalysts for the Slurry-Phase Catalytic Hydrogenation of Anthracene," ACS Omega, vol. 9, no. 22, pp. 23843-23852, May 2024.

[14] E. N. Al-Shafei et al., "Hierarchical ZSM-5@SiO2 Catalysts: A Novel Approach to Optimizing Olefin Yield from Heavy Atmospheric Gas Oil," J. Phys. Chem. C, vol. 128, no. 25, pp. 10440-10449, Jun. 2024.

[15] B. Rabindran Jermy et al., "Crude oil conversion to chemicals over green synthesized ZSM-5 zeolite," Fuel Processing Technology, vol. 241, p. 107610, Mar. 2023.

[16] X. You et al., "Efficacy of Ca/ZSM-5 zeolites derived from precipitated calcium carbonate in the methanol-to-olefin process," Chinese Journal of Structural Chemistry, vol. 43, no. 4, p. 100265, Mar. 2024.

[17] M. F. Ali et al., "Enhancing the selectivity for light olefins through catalytic cracking of n-hexane by phosphorus doping on lanthanum-modified ZSM-5," Frontiers in Chemistry, vol. 12, May 2024.

[18] M. Alabdullah et al., "One-step conversion of crude oil to light olefins using a multi-zone reactor," Nature Catalysis, vol. 4, no. 3, pp. 233-241, Feb. 2021.

[19] "Aramco affiliate S-OIL to build one of the world's largest petrochemical crackers in South Korea." Aramco, Nov. 2022.

[20] Lim Jae-seong, "S-Oil's Shaheen project nears finish, fueling petrochemical ambitions." The Korea Herald, Oct. 2025.

[21] "SABIC Further Optimizes Its Portfolio For Long-Term Sustainable Growth." Hydrocarbononline, 2026.

[22] D. Zhang et al., "Maximization production of light olefins from dual-stage catalytic dehydrogenation cracking of crude oil," Fuel, vol. 375, p. 132570, Nov. 2024.

[23] "Identification and Listing of Hazardous Waste: Spent Catalysts from Dual-Purpose Petroleum Hydroprocessing Reactors." U.S. EPA.

[24] M. Marafi and M. S. Rana, "Role of EDTA on Metal Removal from Refinery Waste Catalysts," WIT Trans. Ecology and Environment, vol. 1, pp. 137-147, Sep. 2018.

[25] K. Hoffmann, "BASF introduces Fourtiva Fluidized Catalytic Cracking catalyst." BASF News Release, Aug. 2024.

[26] U. C. Nwachukwu et al., "Intrinsically Bifunctional and Tunable Tungsten Carbide Catalysts Enable Efficient PVC-Compatible Polyolefin Hydrocracking," J. Am. Chem. Soc., vol. 147, no. 52, pp. 47963-47976, Dec. 2025.

[27] S. M. H. D. Perera et al., "Achieving Phase Control of Polymorphic Tungsten Carbide Catalysts," ACS Catalysis, vol. 16, no. 2, Jan. 2026.

[28] "New catalyst makes plastic upcycling 10x more efficient than platinum." ScienceDaily, Jan. 24, 2026.

[29] B. Yu et al., "Deep Desulfurization of Diesel Oil and Crude Oils by a Newly Isolated Rhodococcus erythropolis Strain," Appl. Environ. Microbiol., vol. 72, no. 1, pp. 54-58, Jan. 2006.

[30] A. Bagchi and P. Srivastava, "Genetic and metabolic engineering approaches for enhanced biodesulfurization of petroleum fractions," Front. Bioeng. Biotechnol., vol. 12, Oct. 2024.

[31] "S-Oil CEO designates 2026 as Year of Shaheen Project Fruition." The Asia Business Daily, Jan. 8, 2026. https://cm.asiae.co.kr/en/article/2026010811415429303

Biographies

Dr. Raj Shah, is a Director at Koehler Instrument Company in New York, where he has worked for the last 25 plus years. He is an elected Fellow by his peers at ASTM, IChemE, ASTM,AOCS, CMI, STLE, AIC, NLGI, INSTMC, Institute of Physics, The Energy Institute and The Royal Society of Chemistry. An ASTM Eagle award recipient, Dr. Shah recently coedited the bestseller, "Fuels and Lubricants handbook", details of which are available at ASTM's Long-awaited Fuels and Lubricants Handbook https://bit.ly/3u2e6GY. He earned his doctorate in Chemical Engineering from The Pennsylvania State University and is a Fellow from The Chartered Management Institute, London. Dr. Shah is also a Chartered Scientist with the Science Council, a Chartered Petroleum Engineer with the Energy Institute and a Chartered Engineer with the Engineering council, UK. Dr. Shah was recently granted the honorific of "Eminent engineer" with Tau beta Pi, the largest engineering society in the USA. He is on the Advisory board of directors at Farmingdale university (Mechanical Technology), Auburn Univ (Tribology), SUNY, Farmingdale, (Engineering Management) and State university of NY, Stony Brook (Chemical engineering/ Material Science and engineering). An Adjunct Professor at the State University of New York, Stony Brook, in the Department of Material Science and Chemical Engineering, Raj also has over 700 publications and has been active in the energy industry for over 3 decades.

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Mr. Daniel Yon is an undergraduate student at Johns Hopkins University pursuing a Bachelor of Science in Chemical and Biomolecular Engineering. He serves as a researcher in the Howard Katz Research Group, where his work focuses on the engineering and characterization of organic electrochemical transistor (OECT) biosensors for precision diagnostics. He is also an intern at Koehler Instrument Company under Dr. Raj Shah in Holtsville, NY.

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