

Review Article

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From Palm Oleochemicals to the Reservoir: Molecular Design, Compatibility Windows and the Missing Path to Field Deployment of Palm-Derived Green Surfactants for Enhanced Oil Recovery- A Critical Review

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ABSTRACT

Palm oil, palm-kernel oil, and oil-palm processing residues provide a potentially strategic renewable platform for chemicals used in enhanced oil recovery (EOR). Among the resulting products, methyl ester sulfonate (MES), lignin-derived lignosulfonates, palm fatty-acid-derived soaps, polymeric surfactants, and biomass-derived alkaline materials have attracted increasing attention because they combine interfacial activity with possibilities for renewable sourcing and local manufacturing. This critical qualitative review evaluates why encouraging laboratory performance has not yet translated into widespread field deployment. The analysis integrates molecular architecture, critical micelle concentration, interfacial tension reduction, phase behavior, wettability alteration, adsorption and retention, salinity and divalent-ion tolerance, thermal stability, surfactant-polymer and alkali-surfactant-polymer formulations, nanoparticle hybrids, environmental performance, manufacturing scalability, and economics. Evidence published during 2020–2026 indicates that palm-derived MES currently has the strongest reservoir-relevant evidence, including performance under high-salinity and elevated-temperature conditions, whereas oil-palm lignosulfonates and palm-biomass-derived alkalis remain at less mature stages. The review argues that low interfacial tension alone is an inadequate criterion for technological readiness. A Palm-EOR Field Readiness Framework is therefore proposed, linking feedstock consistency and molecular function to reservoir compatibility, porous-media transport, formulation engineering, sustainability, techno-economics, pilot qualification, and commercial implementation. Future research should prioritize representative formation brines, reservoir cores, dynamic adsorption, long-duration aging, produced-fluid management, reservoir simulation, life-cycle assessment, and progressively scaled field pilots.

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Introduction

Mature petroleum fields remain important to global energy supply because a substantial fraction of hydrocarbons initially present in many reservoirs remains unrecovered after conventional primary and secondary production. Waterflooding can maintain pressure and displace mobile oil, but microscopic capillary trapping, unfavorable mobility relationships, heterogeneity, and oil-wet or mixed-wet rock surfaces frequently leave considerable residual oil behind. Chemical enhanced oil recovery (CEOR) addresses these constraints by modifying fluid–fluid and fluid–rock interactions through surfactants, polymers, alkalis, or combinations of them. Among these agents, surfactants are particularly important because reductions in oil–water interfacial tension (IFT), modification of wettability, and formation of favorable microemulsion phases can increase capillary number sufficiently to mobilize otherwise trapped oil [1-3].

The attractiveness of surfactant flooding is nevertheless accompanied by an enduring problem: a surfactant that performs excellently in a bottle test does not necessarily remain effective after being exposed to a real reservoir. Formation-water salinity, calcium and magnesium ions, rock mineralogy, elevated temperature, crude-oil composition, adsorption, precipitation, phase trapping, dilution, dispersion, and chemical degradation can progressively

remove active surfactant from the flowing chemical slug. Because surfactants may represent a major component of CEOR chemical expenditure, relatively modest retention can undermine project economics even when laboratory IFT measurements are excellent [4-6].

Environmental and economic concerns associated with conventional petroleum-derived surfactants have consequently stimulated interest in renewable or “green” alternatives. Natural surfactants, biosurfactants, vegetable-oil-derived amphiphiles, and biomass-derived co-chemicals are increasingly investigated for EOR because renewable carbon sources can potentially reduce dependence on fossil-derived specialty chemicals and may provide favorable biodegradability or toxicity profiles [7-13]. Broader assessments of sustainable upstream recovery also show a clear shift toward bio-based chemicals and hybrid formulations, although they emphasize that technical effectiveness, environmental burden, and economic feasibility must be evaluated together rather than independently [14]. These advantages should therefore not be interpreted as proof that every renewable surfactant is environmentally superior. Renewable origin is only one dimension of environmental performance; synthesis reagents, energy demand, purification requirements, toxicity of intermediates, wastewater generation, chemical dosage, land-use implications, and fate in produced water must also be considered.

Palm-based feedstocks occupy an unusual position in this emerging research landscape. Palm oil contains substantial palmitic and oleic fractions, whereas palm-kernel oil is richer in shorter-chain

lauric and myristic fatty acids. Their fatty acids can be esterified into methyl esters and subsequently transformed into surfactants such as methyl ester sulfonate (MES). Palm-processing streams can additionally provide Palm Fatty Acid Distillate (PFAD), lignocellulosic empty fruit bunches (EFB), and ash containing alkaline constituents. These materials create a broader potential “palm EOR chemical platform” extending from relatively purified oleochemical products to waste-derived lignosulfonates and alkaline agents [15,16].

Palm-derived MES is currently the most technically mature member of this platform. Recent experimental evidence demonstrates that MES can remain surface active under relatively severe laboratory conditions. Hakiki et al., for example, reported MES operation at salinities up to 700 mM NaCl and 80°C, an oil–water IFT of approximately 0.02 mN/m at 80°C, wettability alteration toward water-wet conditions, Winsor III microemulsion formation, and increases in capillary number of two to four orders of magnitude [17]. Earlier harsh-condition testing also demonstrated incremental recovery through spontaneous imbibition at 30,000–40,000 ppm salinity and 80°C [18].

Core-flood evidence further strengthens the case for palm-MES while simultaneously exposing the scale-up problem. Ridaliani et al. reported laboratory flooding using palm-oil-derived MES under reservoir-relevant temperature and brine conditions, demonstrating additional recovery after waterflooding [19]. Yet such experiments are still several qualification stages away from reliable commercial deployment because short Berea-core experiments cannot reproduce reservoir-scale heterogeneity, chemical transport over tens to hundreds of metres, long residence times, changing brine composition, well injectivity, crossflow, produced-fluid handling, or field chemical logistics.

A similar evidence asymmetry characterizes other palm-based materials. Oil-palm EFB lignin can be converted into sodium lignosulfonate; very recent work has demonstrated ultrasound-assisted production with useful surfactant characteristics [20]. Lignosulfonate formulations combined with PFAD-derived soap can achieve very low IFT, and nanoparticle-assisted lignosulfonate systems have shown improved recovery performance in laboratory flooding [21,22]. However, contemporary EOR evidence specifically linking an EFB feedstock through standardized synthesis, reservoir-condition testing, dynamic adsorption, core flooding and pilot deployment remains sparse.

Evidence for palm-biomass-derived alkalis is even less mature. Recent green-CEOR reviews recognize agricultural and palm-derived ash as possible low-cost alkaline resources, but much of the primary oil-palm biomass-ash EOR literature predates the contemporary period and has not yet developed into a sustained body of reservoir-specific validation. Consequently, oil-palm biomass ash should not be discussed as if it possessed the same readiness as palm-derived MES. Its strategic importance lies instead in the prospect of converting an agricultural residue into an ASP co-chemical, provided that variability in alkalinity, dissolved metals, scaling potential, solids, geochemical reactions, and produced-water effects can be controlled.

This critical review therefore moves beyond the question of whether palm-derived surfactants can reduce IFT. The central research question is more demanding: why have promising palm-derived EOR chemicals not progressed proportionately from molecular and laboratory demonstrations to repeatable pilot and

commercial field deployment? This question requires integration of surface chemistry, reservoir engineering, materials science, environmental assessment, manufacturing, logistics and economics rather than an isolated comparison of CMC or IFT values.

The review has six objectives. First, it evaluates how palm feedstock composition and molecular architecture govern EOR-relevant physicochemical behavior. Second, it examines IFT reduction, phase behavior, wettability alteration and capillary desaturation mechanisms. Third, it evaluates compatibility with reservoir salinity, hardness, temperature, crude oil and mineral surfaces. Fourth, it assesses combinations with polymers, alkalis, low-salinity brine, cosurfactants and nanoparticles. Fifth, it critically interrogates environmental and economic claims associated with the word “green.” Finally, it develops a field-readiness framework identifying the experimental, engineering and commercial evidence required before palm-derived systems can progress responsibly toward field deployment.

Review Approach and Analytical Scope

This article adopts a Critical Qualitative Literature Review rather than a systematic literature review or meta-analysis. The purpose is consequently interpretative and integrative: it connects findings generated by studies with different experimental designs and evaluates them against the engineering sequence required for field implementation. This approach is appropriate because palm-derived EOR research remains heterogeneous with respect to crude oils, surfactant purity, salinity, temperature, mineralogy, core type, chemical dosage, flooding sequence and reported outcomes. Direct statistical pooling would risk creating artificial comparability between systems that operate under fundamentally different physicochemical conditions.

The contemporary evidence base was prioritized from peer-reviewed journal articles published from 2020 through August 2026. Major themes were developed around surfactant fundamentals, natural and vegetable-oil surfactants, MES, lignosulfonates, reservoir compatibility, adsorption, polymeric systems, ASP, low-salinity flooding, nanoparticles, biosurfactants, sustainability and field application. Recent major reviews were used to connect specialist findings and identify unresolved translation barriers [23].

Particular analytical weight was assigned to studies that progressed beyond simple surface-tension measurements toward reservoir-relevant conditions. Evidence involving formation-brine chemistry, elevated temperature, wettability measurement, adsorption, spontaneous imbibition, reservoir or analogue core flooding, and hybrid formulation was treated as more informative about deployment than evidence restricted to synthesis and characterization. The review nevertheless retains molecular studies because molecular architecture ultimately sets the operating envelope within which reservoir engineering must function.

Importantly, “palm-derived” is used here with chemical precision. Palm-oil or palm-kernel-derived MES is distinguished from general vegetable-oil surfactants. EFB-derived lignosulfonate is distinguished from lignosulfonate originating from kraft black liquor. PFAD-derived soaps are distinguished from purified fatty-acid surfactants. Likewise, oil-palm biomass ash is not treated as chemically equivalent to date-palm ash or other agricultural ashes. This distinction is essential because apparent similarity in feedstock terminology does not establish equivalent elemental composition, dissolved alkalinity, impurities, scaling tendency, or reservoir response.

Palm Resources as a Molecular Platform for Chemical EOR From Fatty Acid Distribution to Surfactant Behavior

The suitability of vegetable oils as surfactant feedstocks originates in their triglyceride-derived fatty-acid architecture. Hydrocarbon-chain length, number and position of double bonds, branching, and the subsequent hydrophilic head group collectively control hydrophobicity, aqueous solubility, micellization, interfacial packing and temperature behavior. Mohammed and Ikiensikimama emphasize that vegetable-oil feedstock selection should therefore consider not merely oil availability but the fatty-acid profile and its relationship with surface activity, thermal stability and oxidative stability. Long-chain monounsaturated fractions may promote useful surface activity, while more saturated structures can offer superior oxidative and thermal robustness.

Palm oil and palm-kernel oil consequently provide different molecular starting points. Palm oil is dominated by C16 and C18 chains, whereas palm-kernel oil contains substantial C12-C14 fractions. These differences affect the packing parameter, hydrophobic interaction and phase behavior of derivatives. They also mean that the phrase “palm-derived surfactant” can conceal substantial chemical diversity. A formulation derived from palm-

kernel methyl esters should therefore not be assumed to have the same optimum salinity, Krafft behavior or adsorption tendency as one derived primarily from palm-oil C16-C18 methyl esters.

Surfactant selection literature demonstrates why this molecular specificity matters. Molecular architecture governs the balance between affinity for water, oil, micelles and mineral surfaces and therefore affects both desirable interfacial activity and undesirable rock retention [24-26]. Modern zwitterionic and tailored surfactants have been engineered specifically to survive high-temperature or high-salinity environments, demonstrating that renewable surfactants must eventually compete against increasingly sophisticated synthetic molecules rather than against a static conventional benchmark [27].

As illustrated in Figure 1, palm-derived EOR performance is a chain of dependencies rather than a single surfactant property. The scheme links biological feedstocks to molecular and formulation design, interfacial behavior, porous-media transport, and ultimately field-level value, thereby clarifying where laboratory performance can be lost during scale-up.

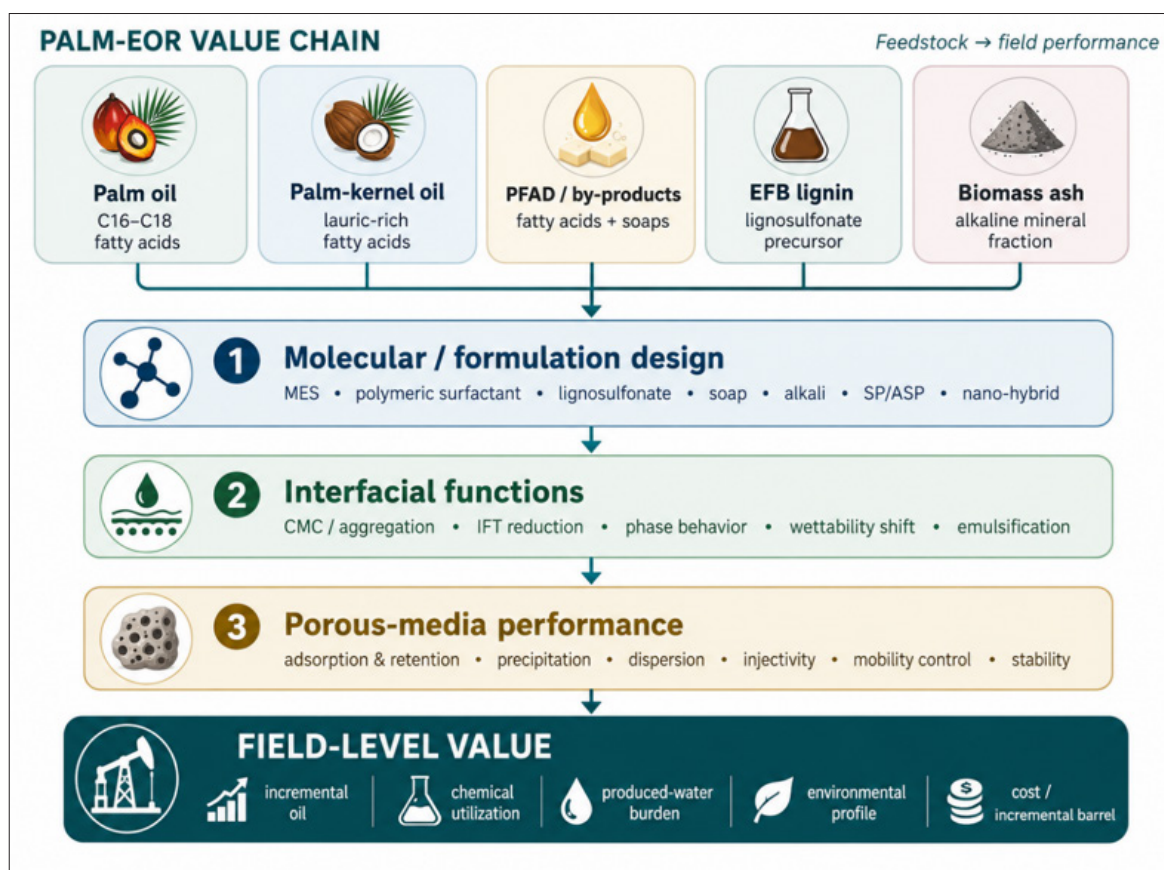


Figure 1: Palm-to-Reservoir Structure Performance Chain
Source: Conceptual Synthesis Developed by the Author Based on Refs.

Figure 1 illustrates why strong laboratory IFT reduction is necessary but insufficient. Every downstream stage can destroy value created upstream. A molecule may possess excellent surface activity but adsorb strongly on clay; a low-cost waste-derived alkali may generate scale; a highly effective ASP formulation may create difficult produced-water emulsions; and a renewable surfactant may become commercially unattractive if large pore-volume concentrations are required. Field readiness is therefore the product of a chain whose weakest link can determine the viability of the complete technology.

Methyl Ester Sulfonate as the Leading Palm-Derived Candidate

MES is particularly attractive because the hydrophobic chain originates from fatty-acid methyl esters while sulfonation introduces an anionic hydrophilic functionality. Palm oleochemical infrastructure already produces fatty-acid and methyl-ester intermediates at industrial scale, creating an advantage over bio-based molecules requiring entirely new manufacturing pathways. Microwave-assisted MES synthesis and related process-development research indicate continued opportunities to modify reaction time, temperature, conversion and product quality [28].

Polymerization or incorporation of polymer functionality offers a further design pathway. Wibowo et al. synthesized polymeric surfactant from palm-oil methyl ester, illustrating the possibility of combining interfacial functionality with molecular architectures intended to improve mobility-control behavior [29]. Such approaches are conceptually important because conventional surfactant flooding often depends on a separate polymer slug to improve macroscopic sweep efficiency, whereas multifunctional molecules could potentially reduce formulation complexity. However, polymeric surfactants bring their own challenges involving molecular-weight distribution, injectivity, mechanical degradation and adsorption [30].

Recent MES studies have importantly shifted the evidence base beyond low-temperature screening. Al Fikri et al. reported recovery behavior under 30,000-40,000 ppm salinity and 80°C, while Hakiki et al. extended the evaluation to high-salinity conditions reaching 700 mM NaCl, 80°C, phase behavior, contact-angle alteration and capillary-number analysis. These studies provide considerably stronger evidence than simple surface-tension tests because they examine several interacting mechanisms under a harsher chemical environment.

Nevertheless, performance at 80°C should not be generalized to all high-temperature reservoirs. Hakiki et al. reported thermogravimetric stability to approximately 90°C followed by progressive decomposition associated with ester functionality at higher temperatures. Reservoir qualification therefore requires distinction between short-duration experimental exposure and long-term stability during injection, transport and residence over months or years. Chemical stability is kinetic as well as thermodynamic, and an acceptable short test can conceal gradual hydrolysis or degradation.

Lignosulfonates and the Circular-Bioeconomy Opportunity

Oil-palm empty fruit bunches represent a large lignocellulosic residue stream. Lignin recovered from this biomass can be chemically modified by sulfonation to produce lignosulfonate-type materials. Qadariyah et al. recently demonstrated ultrasound-assisted sodium-lignosulfonate production from oil-palm EFB lignin, reporting a best experimental yield of approximately 57% and HLB characteristics consistent with surfactant functionality. This development is significant because it potentially links palm waste management, lignin valorization and petroleum-field chemistry.

Evidence from broader lignosulfonate EOR systems illustrates what may be achievable if EFB-derived products can be standardized. Azis et al. developed sodium lignosulfonate from kraft black liquor and formulated it with PFAD soap and octanol. A composition of lignosulfonate: PFAD soap: octanol of 70:22:8 achieved an IFT in the order of 10^{-3} mN/m, demonstrating that lignin-based surfactants can participate in technically strong

interfacial formulations. Dampang et al. further showed that silica nanoparticles can enhance lignosulfonate-assisted flooding, reinforcing the possibility that future palm-waste-derived systems may operate most effectively as engineered mixtures rather than stand-alone molecules.

The critical limitation is provenance and standardization. Strong

EOR performance of a lignosulfonate prepared from kraft black liquor does not prove that EFB-derived lignosulfonate will have identical molecular weight, sulfonation degree, aromaticity, impurity profile or adsorption. The future research sequence should therefore explicitly connect EFB source → lignin isolation → sulfonation degree → molecular distribution → interfacial behavior → adsorption → core flooding. Without this chain, claims about an “EFB lignosulfonate EOR technology” remain ahead of the evidence.

Palm-Biomass Ash and Alkaline Co-Chemicals

Alkali in ASP formulations can reduce surfactant adsorption, alter surface charge and react with acidic crude-oil components to generate surface-active soaps in situ. Biomass ash offers an appealing circular-economy source of alkalinity, especially in regions where palm-processing residues are abundant. Recent reviews categorize agricultural and palm-derived residues among potential green CEOR materials, but also reveal that this research stream is far less mature than contemporary MES development.

A field-oriented evaluation must therefore characterize more than pH. Relevant variables include total alkalinity, carbonate and hydroxide speciation, potassium and sodium concentration, silica, calcium, magnesium, trace metals, suspended solids, batch-to-batch variation, filtration requirements and reactions with formation water. A low-cost alkaline extract that precipitates divalent minerals, plugs near-wellbore pore space or creates difficult produced-water scaling would not be economically “green.” Palm-biomass-ash-derived alkali is thus best characterized as a promising co-chemical research opportunity, not yet as a field-qualified EOR reagent.

From Molecular Architecture to Oil Mobilization Critical Micelle Concentration and the Limits of CMC as a Screening Metric

The critical micelle concentration is routinely used to characterize surfactants because it identifies the concentration range at which aggregation becomes energetically favorable. Below the CMC, increasing surfactant concentration generally increases interfacial adsorption; above it, additional molecules increasingly populate micelles. CMC therefore provides information useful for formulation design, but it should not be interpreted as the optimum field concentration. Reservoir brine composition, crude oil, temperature, cosurfactants and mineral surfaces can all shift effective aggregation and partition behavior [31].

A field formulation frequently operates according to phase-behavior and retention constraints rather than CMC alone. Surfactant lost to rock adsorption must be replenished before the active front can propagate, while excessively high concentration increases chemical cost and can create viscosity, emulsion or separation problems. The economically optimum concentration is therefore a reservoir-system property rather than an intrinsic molecular constant.

Interfacial Tension and Capillary Desaturation

IFT reduction is central to surfactant EOR because capillary forces

trapping oil in pore throats depend directly on interfacial tension. When viscous forces relative to capillary forces increase, trapped ganglia can deform and mobilize. Very low IFT, particularly in the 10^{-2} to 10^{-3} mN/m domain under appropriate conditions, can substantially increase the capillary number. However, IFT should be interpreted together with contact angle, flow velocity and viscosity rather than in isolation.

Hakiki et al. demonstrate this integrated mechanism particularly clearly. MES reduced IFT while simultaneously altering sandstone wettability toward preferentially water-wet conditions, producing a two-to-four-order increase in capillary number. The importance of this finding lies less in any single IFT value than in the demonstration that interfacial and wettability mechanisms act together.

Phase behavior is equally important. Optimum microemulsion conditions can produce favorable solubilization of both oil and water, often associated with Winsor III behavior. Dynamic salinity-based screening offers a route for identifying formulation windows more efficiently than isolated IFT tests [32]. For palm-derived systems, systematic hydrophilic–lipophilic difference and salinity-phase inversion analysis could substantially improve molecular-to-reservoir formulation design.

Wettability Alteration

Reservoir wettability governs the distribution of oil and water on mineral surfaces and therefore strongly influences spontaneous imbibition and displacement efficiency. Carbonate reservoirs present particular challenges because positively charged mineral surfaces and adsorbed acidic crude-oil components can create strongly oil-wet conditions. Surfactant structure, charge and brine composition determine whether adsorbed oil components are removed and whether the surface shifts toward a more favorable intermediate-wet or water-wet state [33].

Low-salinity brine can act synergistically with selected surfactants by modifying surface charge, electrical double layers and ion exchange. Souayeh et al. demonstrated that the effect depends strongly on surfactant class and interactions between nonionic and anionic molecules [34]. Consequently, a palm-derived anionic surfactant that performs effectively in sandstone cannot automatically be transferred to carbonate rock without mineral-specific assessment.

Natural-surfactant research reinforces this system dependence. Saponin-based surfactants can modify wettability in sandstone and carbonate systems, while plant-derived surfactant behavior varies with ions and mineral surfaces [35,36]. Palm-derived molecules should therefore be compared not only against petroleum sulfonates but also against rapidly improving classes of natural and engineered green surfactants.

Reservoir Compatibility: The Critical Qualification Window Salinity and Divalent Ions

Salinity modifies electrostatic screening, micellization, surfactant partitioning, optimal salinity and mineral-surface interactions. For anionic surfactants, moderate salinity can sometimes promote favorable interfacial packing, whereas excessive ionic strength or hardness can induce precipitation or phase instability. Calcium and magnesium deserve particular attention because they can interact more strongly with anionic head groups than monovalent sodium [37].

Studies of hypersaline systems demonstrate that mixed anionic–nonionic formulations can expand the compatibility envelope because the nonionic component can mitigate precipitation and modify interfacial packing [38]. Tailored nonionic or zwitterionic structures likewise illustrate how modern surfactant engineering can improve resilience in hostile brines. A recent synthesis focused specifically on dense carbonates concludes that high salinity, high temperature, strong adsorption, and formation damage remain coupled design constraints, so candidate surfactants should be screened as reservoir-specific formulations rather than as universally transferable products [39]. Palm-MES therefore needs to be evaluated against these high-performance benchmarks rather than judged only by comparison with conventional surfactants under mild laboratory conditions.

Figure 2 emphasizes that reservoir compatibility is a multidimensional operating window. Passing one variable, such as stability at 80°C, does not demonstrate field suitability unless the formulation simultaneously tolerates salinity, divalent ions, mineral surfaces, and crude-oil chemistry without excessive adsorption, precipitation, or degradation.



Figure 2: The Multidimensional Reservoir-Compatibility Window for Palm-Derived Surfactants
Source: Author Synthesis Based on Refs. [40,41].

The figure highlights why a universal “best palm surfactant” is unlikely to exist. Formulation should instead be designed for a specified reservoir envelope. A molecule optimized for a moderate-salinity sandstone may be inappropriate for a high-hardness carbonate, while a formulation designed for offshore high-temperature carbonate conditions may be unnecessarily expensive in a mild onshore sandstone reservoir.

Temperature and Long-Duration Stability

Temperature influences CMC, cloud or Krafft phenomena, reaction kinetics, hydrolysis, viscosity and mineral adsorption. The same temperature can improve interfacial activity while accelerating molecular degradation. Therefore, thermal qualification should measure property retention after aging rather than simply whether the surfactant remains visually soluble at the target temperature. Panthi and Mohanty emphasize formulation design for high-temperature offshore carbonate environments, illustrating the rigor required for harsh reservoirs. Palm-derived candidates should undergo multi-week or multi-month aging at reservoir temperature in representative brines, followed by IFT, phase behavior, chemical composition and adsorption measurements. This is particularly important for ester-containing molecules whose degradation behavior may differ substantially from ether- or sulfonate-dominated synthetic surfactants.

Adsorption and Retention: The Hidden Economic Variable

Adsorption is among the most consequential mechanisms separating laboratory interfacial performance from field economics. Surfactant molecules can adsorb through electrostatic attraction, hydrophobic interactions, ion bridging, or surface complexation on quartz, clays, calcite, and other minerals. Static bottle adsorption provides preliminary information, but dynamic adsorption during core flow is more representative because it incorporates transport, dispersion, and changing surface occupancy. Recent mechanistic reviews further identify retention control as a central economic requirement and emphasize the need to evaluate mixed-surfactant adsorption, low-salinity preflushes, sacrificial agents,

nanoparticles, and other mitigation strategies under reservoir-specific conditions [42].

Adsorption isotherm selection also matters. Langmuir-type models assume relatively homogeneous monolayer adsorption, whereas Freundlich and more complex models can better accommodate heterogeneous surfaces. Uncritical fitting can therefore generate misleading reservoir parameters [43]. Carbonate-specific adsorption studies also show that mineral characterization and experimental design materially affect parameter interpretation, reinforcing the need to connect fitted isotherms with actual rock composition and surface chemistry [44]. For palm-derived surfactants, future studies should report raw concentration-loss data, mineral surface area, brine chemistry, equilibration time, and model uncertainty rather than only an adsorption coefficient.

Liu et al. show that adsorption depends jointly on surfactant characteristics, rock mineralogy, solution chemistry and temperature. Phukan et al. likewise demonstrate that carbonate cement within sandstone can materially alter adsorption and wettability behavior [45]. These findings are particularly important for Indonesian mature reservoirs because “sandstone reservoir” is not a sufficiently precise mineralogical classification for chemical design.

Strategies for reducing adsorption include alkali, salinity gradients, polymers, cosolvents, sacrificial agents and nanoparticles. Liu et al. demonstrated the potential of polyacrylate sacrificial agents, while Koparal et al. investigated polyacrylate-based retention reduction in Berea sandstone [46,47]. Such techniques suggest that a palm-MES project should optimize the complete injection chemistry, rather than merely modifying MES concentration.

Hybrid Formulation Engineering Surfactant Polymer Systems

Microscopic displacement and macroscopic sweep efficiency are different problems. Surfactants mobilize residual oil primarily through IFT and wettability mechanisms, whereas polymers

increase aqueous-phase viscosity and can improve the mobility ratio and sweep of heterogeneous reservoir zones. Surfactant–polymer flooding therefore combines complementary mechanisms, but surfactant–polymer interactions can change viscosity, adsorption, phase behavior, and injectivity [48,49]. Field-oriented reviews of high-temperature, high-salinity carbonate applications show that successful SP design requires simultaneous control of surfactant retention and polymer degradation rather than independent optimization of the two components [50]. Recent natural polymeric-surfactant research also demonstrates the expanding benchmark for sustainable formulations under harsh salinity and temperature, increasing the performance standard that palm-derived multifunctional systems must meet [51].

The implication for palm-derived surfactants is that excellent oil mobilization is of limited value if the mobilized oil is bypassed or if the surfactant slug channels through high-permeability zones. Conversely, increasing polymer concentration can compromise injectivity or increase mechanical degradation. Optimization should therefore use reservoir simulation supported by rheology, core flooding and polymer transport data rather than selecting surfactant and polymer concentrations independently.

ASP and Palm-Derived Chemical Systems

ASP combines three interacting functions: alkali can generate in-situ soap and reduce adsorption; surfactant can lower IFT and alter wettability; and polymer can improve sweep efficiency. Habib et al. identify MES as a promising green alternative within such systems while also emphasizing the complexity of ASP produced water. Highly stable emulsions created by an effective ASP formulation can increase separation difficulty and treatment cost after production.

This produced-fluid problem is frequently underrepresented in laboratory EOR research. Recovery factor is normally treated as the end point, but a field operator must also separate oil and water, manage residual polymer and surfactant, control scaling, reinject or dispose of produced water, and protect downstream facilities. A palm-derived ASP formulation should therefore be evaluated from Injection Tank to Produced Water Discharge or Reinjection, rather than only across a core plug.

Palm-biomass-ash-derived alkali is potentially interesting in this context because the same agricultural value chain could theoretically supply both surfactant and alkaline co-chemical. However, this integration should be pursued only after geochemical compatibility is demonstrated. Variability inherent in ash composition may require purification or blending that erodes the apparent low-cost advantage.

Low Salinity Surfactant Combinations

Low-salinity water can modify mineral surface charge, electrical

double layers, and crude-oil adsorption, thereby creating conditions under which a smaller amount of surfactant may produce an equivalent wettability response. Surfactant-assisted low-salinity studies in carbonates and low-salinity surfactant nanofluids demonstrate potentially synergistic mechanisms, but they also show that performance is strongly formulation- and mineral-specific [52]. The implication is that low-salinity water should be treated as an active formulation variable rather than merely as a diluent for the surfactant slug.

This approach could be particularly relevant for palm-MES. Instead of forcing a single renewable surfactant to withstand all formation-water conditions, engineered preflush or salinity-gradient strategies could modify the reservoir environment before the principal surfactant slug arrives. Such formulation engineering can sometimes be more practical than extensive molecular redesign.

Nanoparticle Assisted Formulations

Nanoparticles have become prominent in EOR because they can modify wettability, stabilize interfaces, influence disjoining pressure and interact with adsorbed surfactant layers. Silica is particularly attractive because surface chemistry can be tuned while particle size allows access to many pore networks. However, nanoparticle stability must be maintained under salinity and temperature conditions to prevent aggregation and plugging [53,54].

Surfactant-assisted functional silica nanofluids have demonstrated wettability modification under low-salinity conditions, while other environmentally oriented nanomaterials have produced favorable effects in carbonate systems [55,56]. Green-surfactant-treated nanoparticles and hybrid alumina/silica systems continue this trend toward multifunctional chemical packages [57,58]. For palm-related systems, Dampang et al. provide an especially relevant bridge by investigating silica-nanoparticle-assisted lignosulfonate flooding. More generally, nanoparticles may reduce surfactant retention at very low dosage. Rebello et al. report that concentrations in the approximate range of 0.001–0.01 wt% have been explored as adsorption-mitigation agents and highlight nanocarriers that reduce direct surfactant–rock interaction while retaining interfacial effectiveness [59].

Figure 3 illustrates a key conclusion of the review: future palm-based EOR is more likely to rely on engineered hybrid formulations than on a one-for-one replacement of a synthetic surfactant with a single “green” molecule. The performance objective is therefore system-level synergy, in which each component improves a distinct limitation without creating an offsetting compatibility or handling problem.

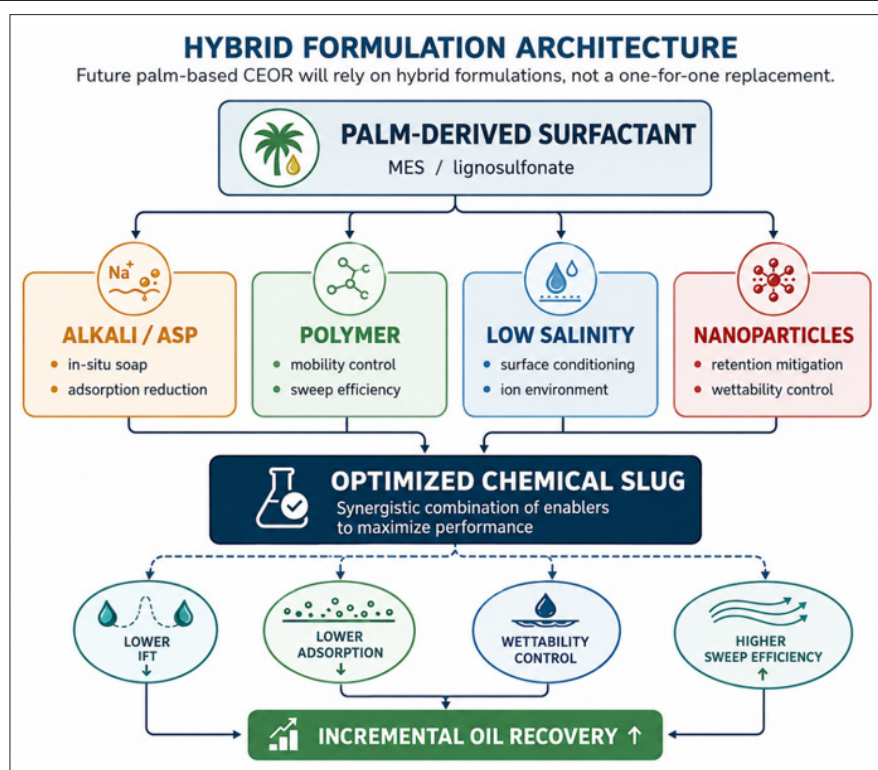


Figure 3: Hybrid Formulation Architecture for Next-Generation Palm-Based CEOR
Source: Author Synthesis Based on Refs [60].

The technological attraction of hybrid systems comes with an equally important qualification burden. Every added component creates additional chemical–chemical and chemical–rock interactions. A formulation containing MES, polymer, alkaline extract and silica nanoparticles must therefore be tested as the complete mixture under reservoir temperature and brine conditions. Component-level compatibility does not guarantee mixture-level stability.

Green Performance: Beyond Renewable Origin

The word “green” should be treated as a hypothesis to be tested rather than a label automatically earned by biological feedstock. Natural and biosurfactant reviews consistently identify biodegradability and potentially lower toxicity as major advantages, but they also recognize constraints involving production cost, purification, consistency and scale.

Vegetable-oil-derived surfactants present an additional paradox. The carbon feedstock may be renewable, but sulfonation, esterification, neutralization and purification can consume fossil energy and chemically intensive reagents. Mohammed and Ikiensikimama therefore argue for broader feedstock screening that considers sustainability, availability and physicochemical suitability. Using a primary edible oil merely because it is renewable may be less attractive than using PFAD, waste cooking oil or lignocellulosic by-products that avoid direct competition with food supply.

For the palm sector, the strongest environmental proposition may consequently lie in Hierarchical Feedstock Use. High-value primary oil should be reserved for applications where its purity or molecular profile is genuinely required, whereas residues and secondary streams should be prioritized where they can deliver acceptable performance. EFB lignin, PFAD and biomass residues are attractive in this respect because EOR could become one

component of a broader palm biorefinery rather than a new demand channel for primary edible oil.

Life-cycle assessment should include plantation inputs, milling, transport, oleochemical conversion, chemical formulation, injection energy, chemical losses, produced-water management and ultimate biodegradation or disposal. Toxicity assessments should use the final formulation rather than the isolated feedstock because cosurfactants, nanoparticles, polymers and alkaline additives may dominate the environmental profile.

Economic assessment requires similar discipline. A lower price per kilogram does not establish a cheaper EOR process. Relevant metrics include kilograms of active surfactant per injected pore volume, retention loss, preparation-water requirement, storage stability, transportation, injection equipment, polymer requirement, incremental oil, produced-fluid treatment, and cost per incremental barrel. Surfactant retention is particularly consequential because lost material simultaneously increases chemical cost and weakens the downstream surfactant front.

El-Masry et al. demonstrate the broadening interest in green CEOR materials while emphasizing that promising laboratory products still require economic and field validation. This conclusion is especially relevant for palm derivatives. Indonesia’s large oleochemical industry creates plausible supply-chain advantages, but these advantages become commercially meaningful only if field dosage, purity requirements and logistics are quantified.

Why Has the Laboratory Success Not Become Field Deployment?

The Representativeness Gap

The first barrier is that many laboratory studies test an idealized system. Synthetic NaCl brine may replace actual formation water; Berea sandstone may replace reservoir core; a model oil

may substitute for field crude; short experiments replace long residence time; and mineralogical heterogeneity is minimized. Such experiments are necessary for mechanism identification but insufficient for project sanction.

A reservoir-fluid system is path-dependent. Surfactant may encounter injection water, completion chemicals, residual scale inhibitor, clay-rich laminations, high-calcium formation water and crude oil with locally variable acid number. Each encounter can shift phase behavior or adsorption. Massarweh and Abushaikh show the importance of combining physicochemical characterization with core flooding when evaluating surfactants in tight carbonates, illustrating the need for a much more integrated qualification process [61].

Palm-MES research has begun moving toward harsher and more representative conditions, but the evidence still predominantly remains at laboratory scale. Lessons synthesized from SP and ASP coreflood studies show that recovery outcomes are highly sensitive to core properties, fluid preparation, surfactant selection, slug design, and test sequence, which limits the transferability of isolated recovery-factor values across reservoirs [62]. The logical next stage is therefore not another ambient-temperature IFT study. It is long-core flooding using native-state or restored-state reservoir cores, actual or rigorously reconstructed formation brines, representative crude oil, reservoir temperature and pressure, followed by measurement of effluent surfactant concentration and material balance.

The Metric Gap

A second barrier is overreliance on convenient metrics. Surface tension, CMC, contact angle and equilibrium IFT are scientifically useful, but no single one predicts field recovery. Even ultralow IFT can coexist with unacceptable adsorption. Contact-angle improvement can coexist with precipitation. High recovery from a small homogeneous core can coexist with poor mobility control in a heterogeneous reservoir.

The minimum laboratory evidence package should therefore include: chemical composition; active matter; phase behavior; CMC or aggregation behavior; IFT as a function of salinity and temperature; wettability; static and dynamic adsorption; precipitation boundaries; long-term thermal stability; rheology with polymer where applicable; core pressure drop; injectivity; surfactant breakthrough; incremental recovery; and produced-fluid characteristics. Nadir et al. and Chowdhury and Sangwai illustrate why phase behavior and interfacial assessment must be interpreted together rather than as independent rankings.

The Adsorption and Transport Gap

Surfactant reaching the injection well is not the same as surfactant reaching residual oil deep in the formation. Adsorption, precipitation and phase trapping progressively retard the chemical front. Kalam et al. explicitly identify these mechanisms as central surfactant-retention pathways. Liu et al. similarly demonstrate that mineral surface chemistry can dominate performance.

Field-oriented research should therefore construct dynamic retention curves and incorporate them into chemical-transport simulators. Retention should be measured over multiple pore volumes, with realistic mineralogy and salinity gradients. Effluent analysis should distinguish intact surfactant from degradation products. This requirement is particularly important for bio-derived products because commercial material may contain homolog distributions and impurities not represented by a single pure model compound.

The Manufacturing Consistency Gap

Laboratory synthesis can carefully control reaction temperature, molar ratios and purification. Industrial production must do so continuously or in large batches while managing feedstock variability. Palm fatty-acid distributions vary with feedstock stream and processing conditions, while lignin-derived products can vary even more strongly in molecular weight and functionalization. Qadariah et al. demonstrate that MES synthesis parameters materially influence product formation, while Wibowo et al. illustrate additional complexity when polymer functionality is introduced. EFB lignosulfonate introduces another level of variability because lignin isolation and sulfonation determine molecular properties.

Field specifications must consequently be defined in measurable terms: active matter, chain-length distribution, unsulfonated material, inorganic salts, water content, pH, viscosity, molecular-weight distribution, sulfonation degree and storage stability. Without such specifications, a successful laboratory formulation cannot be reproduced reliably at thousands-of-tonnes scale.

The formulation Complexity Gap

EOR projects frequently optimize chemicals sequentially: first surfactant, then polymer, then alkali. Yet the reservoir receives the coupled formulation. Interactions may change polymer viscosity, microemulsion phase behavior, adsorption or precipitation. ASP systems can additionally produce persistent emulsions that complicate surface processing.

Nanoparticle hybrids intensify this issue. Nanoparticles can beneficially reduce adsorption or alter wettability, but instability can cause aggregation and pore blockage. Reviews by Al-Asadi et al., Lashari et al., Maia et al., Deshmukh and Pathan and Rebello et al. indicate substantial innovation while simultaneously underscoring the need for reservoir-specific validation.

The Environmental Accounting Gap

Biodegradability in fresh water at ambient conditions is not enough to establish environmentally benign field behavior. Produced water may contain high salinity, hydrocarbons, metals, polymer, nanoparticles and degradation products. Offshore discharge rules can impose particularly demanding toxicity and biodegradation criteria.

Green-CEOR evaluation should therefore compare complete formulations using standardized ecotoxicity, biodegradation and life-cycle indicators. Al-Ghamdi et al. and El-Masry et al. provide important frameworks for this broader environmental orientation, while Abdurrahman et al. demonstrates the wider petroleum-industry interest in environmentally compatible natural surfactants.

The Economic and Logistics Gap

Field deployment transforms a laboratory reagent into a supply-chain problem. A surfactant may need to be produced continuously, transported to a remote field, stored under tropical conditions, dissolved reproducibly in field water, mixed without excessive foam, injected for months and supported by quality-control laboratories.

The economic question is consequently not whether palm surfactant is inexpensive per kilogram, but whether the total formulation produces additional barrels at an acceptable risk-adjusted cost. Adsorption, concentration, slug size and polymer dosage are primary drivers. A small reduction in required surfactant concentration can be more valuable than a substantial reduction in purchase price.

The Pilot Evidence Gap

The final and most visible gap is the shortage of documented field pilots for vegetable-oil-derived surfactants. Mohammed and Ikiensikimama explicitly concluded that vegetable-oil surfactants had not yet achieved meaningful field application, while a critical review of carbonate surfactant projects shows that field-scale design requires sequential screening of reservoir temperature, salinity, permeability, wettability, and chemical compatibility rather than reliance on a single laboratory metric [63]. The latest broad surfactant review by Pereira et al. similarly highlights reservoir-specific formulation, adsorption, transport, and laboratory-to-field translation as central contemporary challenges.

The appropriate response is not to overstate laboratory results but to construct a staged pilot pathway. Laboratory evidence should progressively reduce uncertainty until a limited field pattern can test injectivity, chemical breakthrough, incremental production, produced-water behavior and economic assumptions.

Figure 4 summarizes the central critical contribution of this review by depicting the “valley of death” between impressive laboratory metrics and a bankable chemical-EOR project. The figure makes explicit that integrated qualification, rather than additional molecular novelty alone, is required to bridge core-scale success to field pilots and repeatable deployment.

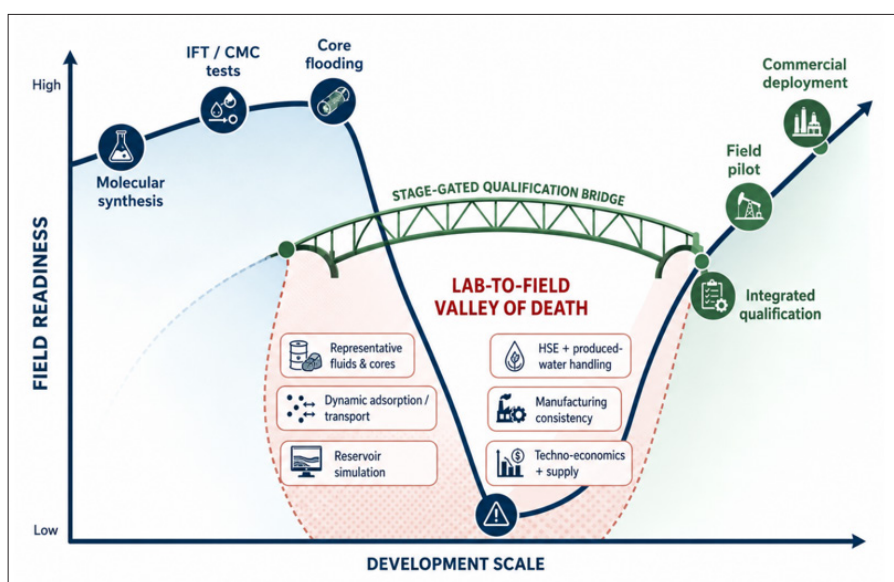


Figure 4: The Palm-EOR Laboratory-to-Field Valley of Death

Source: Author Developed Synthesis Based on Refs.

The figure explains why additional laboratory novelty alone may contribute little to deployment. The highest-value research now lies in systematically de-risking the valley: representative cores, dynamic adsorption, pilot-scale manufacturing, simulation, environmental qualification, produced-fluid evaluation and field economics.

A Palm-EOR Field Readiness Framework

To organize this transition, this review proposes the Palm-EOR Field Readiness Framework (PEFRF). It differs from conventional technology-readiness scales by explicitly requiring evidence to propagate from feedstock and molecular consistency through reservoir and commercial performance.

- **P1- Feedstock and Molecular Feasibility**
The chemical identity, feedstock range, synthesis route, purity and basic surface activity must be established. Palm-oil, palm-kernel-oil, PFAD or EFB provenance should be reported rather than using the generic description “bio-based.”
- **P2 -Interfacial Feasibility**
CMC, IFT, phase behavior and wettability should be characterized across salinity and temperature rather than at one screening condition. Molecular structure–property relationships should be sufficiently understood to allow rational formulation adjustment.
- **P3 -Reservoir Compatibility**
Solubility, precipitation boundaries, hardness tolerance,
- **P4 -Rock–Fluid Compatibility**
Static and dynamic adsorption, formation damage, mineral-specific response and surfactant transport must be quantified. Retention minimization should be formulation-based and supported by mechanistic evidence
- **P5- Representative Core Performance**
Core flooding should progress from Berea or generic carbonate plugs to actual reservoir cores using representative crude and formation brine. Pressure-drop, breakthrough, mass balance and post-flood residual oil saturation should accompany recovery factor.
- **P6- Integrated Formulation Qualification**
SP, ASP, low-salinity or nanoparticle systems should be tested as complete formulations. Chemical interactions, rheology, injectivity, emulsion behavior and produced-fluid treatment must be evaluated.
- **P7- Reservoir Simulation and Techno-Economic Qualification**
Dynamic adsorption, relative permeability, capillary desaturation and chemical propagation should be included in reservoir simulation. Chemical consumption, supply logistics, water treatment and uncertainty in incremental recovery should enter project economics.
- **P8- Field Pilot**

- A limited-pattern pilot should demonstrate sustained injectivity, chemical propagation, measurable incremental oil, manageable produced fluids, and the absence of unacceptable formation damage or environmental effects. Pilot design should also include tracer or chemical monitoring sufficient to distinguish genuine reservoir response from short-term production variability.
- P9- Repeatable Commercial Deployment
Commercial readiness requires successful replication beyond a single pilot, industrial-scale manufacturing quality control, and economics robust to changes in oil price and chemical

demand. At this stage, the formulation should be supported by repeatable supply specifications, operating procedures, produced-fluid management plans, and evidence that performance can be transferred to comparable reservoir settings.

Figure 5 converts the review's major evidence gaps into a practical development roadmap. By positioning molecular feasibility, reservoir proof, integrated qualification, pilot testing, and commercial replication on one readiness ladder, it clarifies which evidence is missing for each palm-derived chemical family.

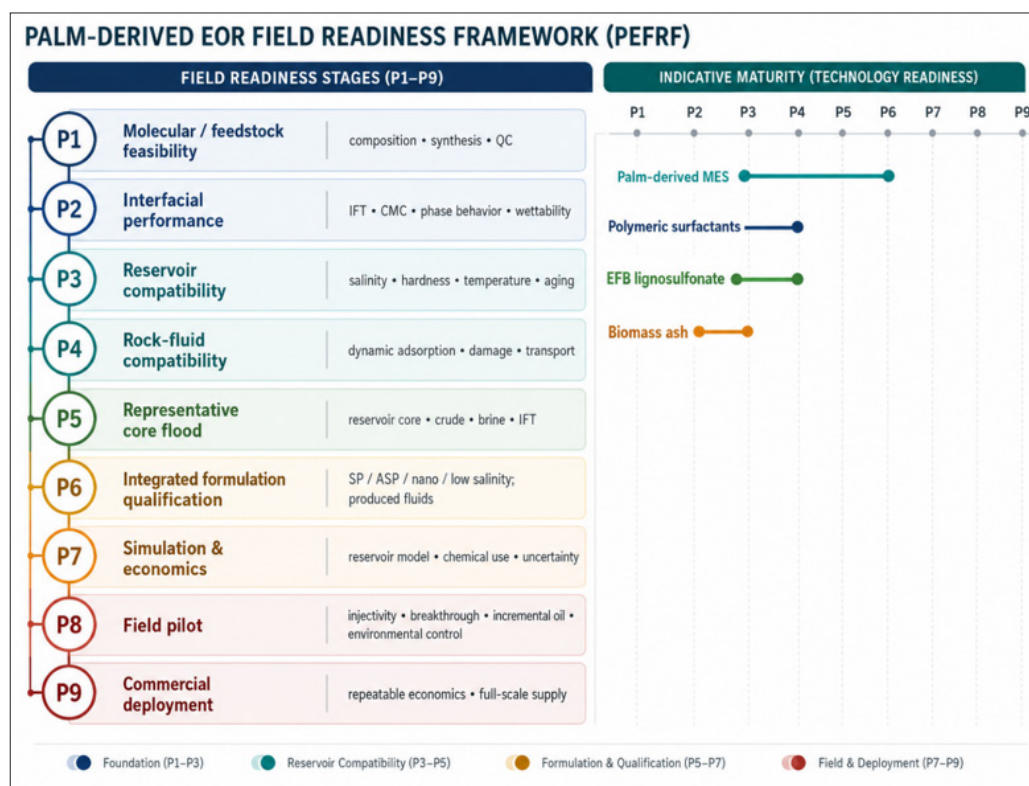


Figure 5: Palm-EOR Field Readiness Ladder

The readiness assessment is deliberately indicative rather than a formal technology-readiness certification. Palm-derived MES currently occupies approximately P3-P5 depending on formulation and reservoir conditions, palm-derived polymeric surfactants and oil-palm EFB-derived lignosulfonates remain approximately P1-P3, and palm-biomass-derived alkalis remain approximately P1-P2 in the contemporary evidence base.

The framework prevents the common mistake of equating a positive core-flood result with commercial readiness. It also exposes where funding should be concentrated. For palm-MES, the scientific priority is increasingly P4–P8 rather than repeated P1-P2 characterization. For EFB lignosulfonate and palm-biomass alkali, more fundamental reproducibility and reservoir-compatibility work remain necessary.

Strategic Implications for Indonesia

Indonesia provides an unusually compelling setting in which to test the palm-EOR proposition. The country simultaneously possesses a large oil-palm value chain, substantial oleochemical manufacturing capacity and numerous mature hydrocarbon fields where improved recovery is strategically important. This co-location could reduce dependence on imported specialty chemicals while creating higher-value applications for domestic oleochemical products and palm-processing residues.

The most credible near-term strategy is not to create an entirely new surfactant industry for EOR but to leverage existing methyl ester and oleochemical capabilities. Palm-derived MES therefore provides the most plausible first candidate for reservoir qualification. Industrial familiarity with methyl ester production can potentially facilitate feedstock control, scale-up and cost reduction relative to novel laboratory biosurfactants whose fermentation and purification infrastructure is less established.

A second strategic opportunity lies in circularity. EFB lignin, PFAD and other secondary streams can potentially enter oilfield-chemical value chains rather than being treated solely as low-value residues. Azis et al. illustrates how PFAD-derived soap can contribute to an ultralow-IFT lignosulfonate formulation, while Qadariyah et al. establishes a contemporary pathway for producing lignosulfonate directly from EFB lignin. Together, these studies suggest a possible future palm biorefinery in which different feedstock fractions are directed toward different EOR functions.

Nevertheless, policy should avoid assuming that domestic origin guarantees lower project cost. Chemical EOR is highly sensitive to reservoir-specific performance. A locally produced surfactant that requires twice the concentration or experiences substantially greater adsorption than an imported alternative may increase rather than reduce life-cycle cost. Local-content strategy should therefore be performance-based, supported by standardized testing and field pilots.

A productive national research model would connect oleochemical producers, palm-biomass processors, universities, research laboratories and petroleum operators around one or more selected mature reservoirs. Instead of each institution conducting isolated IFT studies, an integrated program could define a real target reservoir, obtain representative crude and core, optimize a palm-derived formulation, manufacture a pilot batch, conduct long-core and simulation studies, and progress toward a controlled field pilot.

Such a program would also generate more internationally valuable scientific evidence. The next major contribution from Indonesia need not be another demonstration that palm MES lowers IFT; it could be the first rigorously documented development sequence demonstrating how a renewable palm-derived CEOR formulation moves from industrial feedstock specification through porous-media qualification to field performance.

Future Research Agenda

The first research priority is Standardization of Palm Derived Chemicals. Studies should report feedstock origin, fatty-acid distribution, active matter, chain-length distribution, impurities and batch-to-batch reproducibility. For EFB lignosulfonates, molecular weight, polydispersity, sulfur content, degree of sulfonation and residual ash should become standard characterization variables. Second, reservoir screening should use a Compatibility Map Approach. Rather than reporting performance at a single salinity and temperature, studies should construct response surfaces covering NaCl, Ca²⁺, Mg²⁺, temperature, pH and surfactant concentration. This would reveal the boundaries separating desirable phase behavior from precipitation or performance collapse.

Third, dynamic adsorption should become routine. Abbas et al., Kalam et al., Liu et al., Koparal et al. and Phukan et al. collectively show that adsorption is too consequential to remain an optional measurement. Static adsorption can screen formulations, but long-core dynamic retention provides the information required for simulation and economics.

Fourth, palm-MES research should move into long-duration thermal and chemical aging. Hakiki et al. provide important contemporary evidence at 80°C, but field qualification requires confirmation that interfacial activity survives realistic residence times. Samples aged for weeks or months should be chemically analyzed and retested for IFT, phase behavior, adsorption, and degradation products.

Fifth, future experiments should distinguish sandstone subtypes and carbonate subtypes rather than treating mineral classes as homogeneous. Clay fraction, carbonate cement, calcite/dolomite ratio and surface area can dominate adsorption and wettability response.

Sixth, hybrid formulation research should progress from demonstrating synergy to identifying net economic benefit. Nanoparticles can reduce retention or improve wettability, but additional material cost, dispersion preparation, potential aggregation and produced-water fate must be considered. Similarly, polymeric surfactants and SP/ASP formulations must be judged against total chemical utilization and injectivity rather than maximum laboratory recovery alone.

Seventh, environmental research should evaluate the complete injected and produced formulation. Claims of biodegradability for MES or lignosulfonate are insufficient if the operational mixture also contains persistent polymer, cosolvent, nanoparticle, or biocide. Standard aquatic toxicity, biodegradation, and life-cycle assessment should therefore accompany field-pilot preparation. Eighth, reservoir simulation should be introduced earlier. Laboratory measurements of adsorption, phase behavior and capillary desaturation should populate mechanistic chemical-EOR models. Sensitivity analysis can then quantify which uncertainties adsorption, concentration, slug size, heterogeneity, polymer viscosity or chemical degradation most strongly affect incremental recovery and project economics.

Finally, field deployment should use a Stage Gated Learning Strategy. The first pilot does not need to prove immediate nationwide commercial viability. It should be designed to generate maximum information about injectivity, surfactant propagation, adsorption, produced-fluid response and incremental recovery. A well-instrumented pilot that reveals why a formulation underperformed may be scientifically and commercially more valuable than another laboratory experiment demonstrating a record-low IFT.

Conclusion

Palm-derived chemicals offer a technically credible and strategically relevant platform for greener chemical enhanced oil recovery, but the different members of this platform are not equally mature. Palm-derived methyl ester sulfonate presently has the strongest evidence because contemporary studies demonstrate IFT reduction, wettability alteration, and recovery behavior under increasingly demanding salinity and temperature conditions. EFB-derived lignosulfonate represents a promising circular-economy pathway but still requires a stronger direct bridge from EFB-specific molecular properties to reservoir performance. Palm-biomass-derived alkaline chemicals remain at an earlier stage of modern development.

The most important conclusion is therefore not simply that palm-derived surfactants “work.” Many laboratory studies already demonstrate technical potential. The more consequential issue is whether their functionality persists after exposure to real formation water, divalent ions, reservoir minerals, temperature, chemical aging, porous-media transport, heterogeneous flow, and surface-production systems. Adsorption and retention are especially important because they directly connect molecular chemistry with field economics.

Future research should consequently shift from isolated performance records toward compatibility envelopes and field

qualification. Low IFT must be accompanied by low retention, long-term stability, acceptable injectivity, manageable produced fluids, repeatable industrial quality, and favorable cost per incremental barrel. The proposed Palm-EOR Field Readiness Framework organizes this progression into nine stages extending from feedstock characterization to repeated commercial deployment.

For Indonesia, the opportunity is unusually significant. Existing oleochemical capability, abundant palm-biomass streams and a portfolio of mature oil fields create conditions for a domestic innovation chain connecting palm-based biorefineries with reservoir engineering. The decisive next step, however, is not another claim that a palm derivative is environmentally friendly because it originates from renewable biomass. It is the disciplined demonstration that a reproducibly manufactured palm-derived formulation can survive the complete journey from molecular design to reservoir transport, produced-fluid management, pilot economics and repeatable field performance. Closing that journey constitutes the missing path to field deployment.

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