

Waste Cooking Oil-Derived Methyl Ester Sulfonate for Enhanced Oil Recovery: A Short Review

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Abstract

The increasing demand for sustainable chemical enhanced oil recovery (EOR) has encouraged the development of bio-based surfactants from renewable and low-cost feedstocks. Methyl ester sulfonate (MES) derived from waste cooking oil (WCO) is a promising alternative because of its surface activity and potential contribution to waste valorization. This study presents a structured narrative review linking WCO characteristics, transesterification, MES synthesis, and EOR performance. The reviewed studies indicate that free fatty acid content, moisture, oxidation products, and impurities strongly affect FAME quality and subsequent MES synthesis. Alkali-catalyzed transesterification was commonly reported at 60–65 °C using methanol-to-oil molar ratios of 6:1–9:1 and approximately 1 wt% catalyst. Continuous SO₃-based sulfonation generally provides higher process efficiency and MES quality, whereas NaHSO₃-based processes offer simpler laboratory-scale operation. Reported MES-based systems showed substantial reductions in oil–water interfacial tension and incremental oil recoveries of approximately 25–69% under different experimental conditions. However, direct comparison remains limited by the small number of studies covering the complete WCO–FAME–MES–EOR pathway and by differences in formulations and test conditions. Future studies should integrate standardized feedstock characterization, FAME and MES quality assessment, and reservoir-relevant testing within the same experimental framework.

Keywords: *Methyl Ester Sulfonate, Waste Cooking Oil, Chemical Enhanced Oil Recovery, Sulfonation, Transesterification*

INTRODUCTION

The necessity for Enhanced Oil Recovery (EOR) technologies to maximize hydrocarbon recovery beyond primary and secondary production stages has become increasingly important due to rising global energy demand and the declining productivity of mature oil reservoirs (Hakiki et al., 2026). Among the available EOR techniques, surfactant flooding has received considerable attention because surfactants effectively reduce oil–water interfacial tension (IFT), modify reservoir wettability, and enhance the mobilization of residual oil trapped within porous media (Habib et al., 2024).

Methyl ester sulfonate (MES) has received increasing attention as a bio-based anionic surfactant because of its biodegradability, surface activity, and reported stability under saline and elevated-temperature conditions (Hakiki et al., 2026). Furthermore, renewable lipid feedstocks such as waste cooking oil (WCO) provide an economical and environmentally sustainable raw material for MES production, supporting waste valorization and circular bioeconomy strategies (Beghetto, 2025).

Previous reviews have primarily examined waste cooking oil (WCO) conversion into biodiesel, MES synthesis, or the application of bio-based surfactants for enhanced oil recovery (EOR) as separate topics, leaving the relationships among these stages insufficiently addressed

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(Beghetto, 2025; Habib et al., 2024). A key knowledge gap remains regarding how WCO degradation, including elevated free fatty acids, moisture, oxidation products, and impurities, influences FAME quality, sulfonation efficiency, MES active matter, and ultimately EOR performance (Kumar et al., 2025; Qadariyah et al., 2024). Furthermore, quantitative links between feedstock pretreatment, synthesis parameters, and EOR indicators such as interfacial tension, brine compatibility, and oil recovery are still rarely established (Hakiki et al., 2026; Yusuff et al., 2024). This review addresses these gaps by integrating WCO quality, transesterification, sulfonation, and MES performance into a unified cause-and-effect framework, while critically comparing synthesis strategies and identifying future priorities for feedstock–process–property–performance optimization.

Review Methodology

This study employed a structured narrative review to examine waste cooking oil (WCO)-derived methyl ester sulfonate (MES) for enhanced oil recovery (EOR). The review focused on the feedstock–process–property–performance relationship, covering WCO characteristics and pretreatment, FAME production, MES synthesis and properties, and EOR performance.

Relevant peer-reviewed literature was identified primarily through Scopus, with supplementary searches conducted using ScienceDirect, SpringerLink, Wiley Online Library, and Taylor & Francis Online. Search terms included combinations of “waste cooking oil,” “FAME,” “transesterification,” “methyl ester sulfonate,” “sulfonation,” “enhanced oil recovery,” “interfacial tension,” and “oil recovery.” The identified studies were screened for their relevance to WCO feedstock quality, FAME production, MES synthesis, and EOR applications. Most of the reviewed literature was published between 2021 and 2026.

Direct studies addressing the WCO–FAME–MES–EOR pathway were prioritized. Because studies covering the complete pathway remain limited, related MES and green sulfonate studies were also included as comparative references when relevant to the analysis. Information was extracted on feedstock characteristics, pretreatment methods, transesterification conditions, sulfonation strategies, MES properties, and EOR indicators such as interfacial tension, adsorption, wettability alteration, brine compatibility, and incremental oil recovery.

The selected studies were comparatively analyzed to identify consistent trends, differences among reported findings, and relationships between the processing stages. Particular attention was given to identifying gaps in the quantitative links between WCO quality, FAME characteristics, MES properties, and final EOR performance. The overall review procedure is summarized in Figure 1.

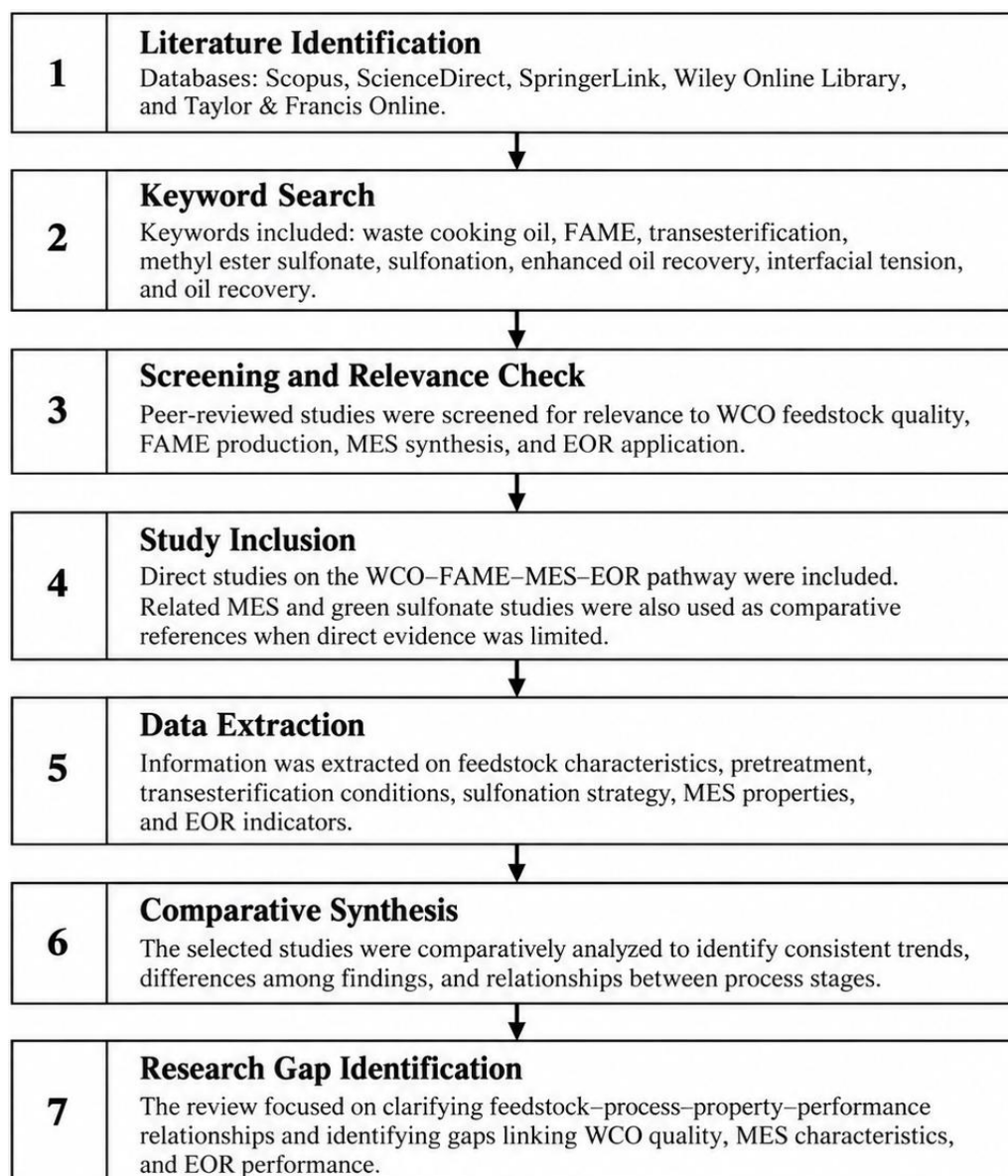


Figure 1. Review Procedure Flowchart

LITERATURE REVIEW

Characteristics of WCO and Pretreatment

Waste cooking oil (WCO) is an attractive feedstock for methyl ester sulfonate (MES) because it supports waste valorization and avoids competition with edible oils. However, repeated heating causes hydrolysis, oxidation, polymerization, and thermal degradation that alter its reactivity and reduce feedstock quality (Beghetto, 2025; Razzak et al., 2025). Consequently, WCO quality is highly variable and may substantially influence both fatty acid methyl ester (FAME) production and subsequent MES synthesis.

Among the relevant quality parameters, free fatty acid (FFA) and moisture reduce FAME yield by promoting saponification, while oxidation products, thermal degradation, impurities, and high peroxide value decrease FAME stability and sulfonation efficiency (Bostan et al., 2024; Haq et al., 2021; Lopresto, 2024; Mishra et al., 2023). Therefore, WCO suitability should be evaluated using comprehensive physicochemical characteristics rather than FFA alone. These variations may explain the inconsistent FAME yields and qualities reported under otherwise comparable transesterification conditions. The major WCO characteristics affecting FAME formation and MES

synthesis are summarized in Table 1.

Table 1. Characteristics of Waste Cooking Oil (WCO) and Its Impact on FAME Formation and MES Synthesis

No.	Parameter	Impact on FAME Formation and MES Synthesis	Reference
1	Free Fatty Acid (FFA)	Causes soap formation, consumes catalyst, and lowers FAME yield and purity.	(Haq et al., 2021)
2	Oxidation Level	Produces degradation compounds that reduce FAME stability and increase side reactions.	(Mishra et al., 2023)
3	Thermal Degradation	Generates altered triglycerides that are harder to convert into stable methyl esters.	(Awogbemi et al., 2019)
4	Impurities	Interfere with catalyst and contaminate FAME, requiring prior purification.	(Bostan et al., 2024)
5	Peroxide Value	Indicates oxidation level, reducing stability and increasing degradation risk.	(Lopresto, 2024)

The influence of WCO quality extends beyond the transesterification stage because the resulting FAME serves as the direct precursor for MES synthesis. High-purity FAME with low levels of residual glycerides, moisture, soaps, impurities, and oxidation products provides a more suitable substrate for sulfonation, whereas unreacted triglycerides and degradation products may increase side reactions and reduce the formation of active sulfonated species. Therefore, WCO pretreatment and transesterification should not be evaluated solely in terms of FAME yield, but also according to the quality requirements of the downstream sulfonation process.

This perspective is particularly important because most studies assess WCO pretreatment and transesterification primarily based on biodiesel yield, while their downstream effects on MES quality and EOR performance remain less systematically evaluated ([Qadariyah et al., 2024](#)). Thus, FAME purity can be considered an important intermediate quality indicator linking WCO characteristics with MES synthesis and, ultimately, surfactant performance.

Pretreatment should therefore target the dominant degradation mechanism, with acid esterification reducing FFA and filtration, adsorption, drying, and decolorization removing impurities, oxidation products, and moisture ([Bostan et al., 2024](#)). However, excessive pretreatment may increase costs without proportional improvements in FAME quality. Since residual glycerides, water, soaps, and oxidized compounds adversely affect sulfonation, pretreatment should be evaluated based on its downstream impact on MES active matter, di-salt formation, color, solubility, and interfacial performance rather than FAME yield alone.

Transesterification conditions and FAME Quality

Table 2 shows that efficient transesterification of waste cooking oil (WCO) is achieved through the combined optimization of catalyst loading, reaction temperature, methanol-to-oil molar ratio, and feedstock quality.

Table 2. Reported Transesterification Conditions for Alkali-Catalyzed WCO Transesterification

No	Catalyst (wt%)	Temp. (°C)	Methanol: Oil	Time (min)	Yield (%)	FAME and subsequent MES synthesis	Reference
1	KOH (1.0)	60	6:1	120	90	Higher methanol improves equilibrium shift toward FAME	(Mercy Nisha Pauline et al., 2021)
2	KOH (0.75–1.25)	55–65	6–12:1	60–120	90.5–97.0	Catalyst level strongly affects ester purity and soap formation	(Rocha-Meneses et al., 2023)
3	KOH (1.0)	55	6:1	90	96.91–97.09	Excess catalyst increases conversion but promotes saponification	(Haq et al., 2021)
4	NaOH (1.0)	60	6:1	70	95.0	Moisture control critical for high biodiesel yield	(Cerón Ferrusca et al., 2023)
5	NaOH (1.0)	60	6:1	60	94.8	Economical route after esterification for high-FFA WCO	(Farouk et al., 2024)

The reviewed studies commonly reported transesterification temperatures of approximately 60–65 °C, providing favorable reaction kinetics while limiting excessive methanol evaporation. ([Miyuranga et al., 2023](#)). A methanol-to-oil ratio of 6:1–9:1 generally improves FAME conversion by shifting the reaction equilibrium, although excessive methanol complicates glycerol separation and downstream purification ([Mercy Nisha Pauline et al., 2021](#)). Similarly, increasing alkaline catalyst concentration enhances triglyceride conversion, but excessive KOH or NaOH promotes saponification, particularly in WCO with high free fatty acid and moisture contents, reducing FAME purity ([Rocha-Meneses et al., 2023](#)). Therefore, approximately 1 wt% catalyst, a 6:1–9:1 methanol-to-oil ratio, and 60–65 °C represent practical operating conditions rather than universally optimal conditions. Final process optimization should consider WCO quality and FAME purity to ensure efficient subsequent MES synthesis ([Farouk et al., 2024](#)). Most transesterification studies report FAME yield rather than precursor-quality parameters relevant to subsequent sulfonation, representing an important limitation in establishing the WCO–FAME–MES relationship.

Sulfonation Strategies and MES Quality

MES is synthesized by sulfonating FAME using sulfur trioxide (SO₃), sodium bisulfite (NaHSO₃), or chlorosulfonic acid, followed by neutralization and purification ([Siwayanan et al., 2021](#); [Yusuff et al., 2023](#)). SO₃-based reactors generally produce higher active matter and lower di-

salt formation but require dry, high-purity FAME (Beghetto, 2025; Mansur et al., 2025). In contrast, NaHSO₃-based batch processes are simpler but more susceptible to by-product formation, while microwave-assisted sulfonation improves heating efficiency although industrial applicability remains uncertain (Qadariyah et al., 2024; Yusuff et al., 2023). Optimum sulfonation conditions should therefore be evaluated using active matter, di-salt content, color, solubility, critical micelle concentration, and interfacial tension rather than conversion alone (Mansur et al., 2025; Yavrukova et al., 2024). For EOR applications, reservoir-relevant testing should also include brine compatibility, adsorption, wettability alteration, thermal stability, and core-flood oil recovery (Habib et al., 2024; Hakiki et al., 2026; Yusuff et al., 2024).

Table 3 indicates that the sulfonation strategy strongly influences methyl ester sulfonate (MES) quality through its effects on active matter, by-product formation, and process efficiency.

Table 3. Comparison of Sulfonation Technologies for MES Production

No	Sulfonating agent	Reactor	Operating conditions	Main advantages	Main limitations	Reference
1	NaHSO ₃	Stirred batch reactor	100–120 °C; 2–5 h	Simple, low cost, easy operation	Slow, lower quality, more di-salt	(Yusuff et al., 2023)
2	NaHSO ₃	Microwave batch reactor	300-750 Watts; 20–60 min	Fast heating, energy efficient	Limited scale, uneven heating	(Qadariyah et al., 2024)
3	SO ₃ gas	Falling-film reactor	60–90 °C; 2 h	High active matter, efficient transfer	Needs dry feed, complex SO ₃ handling	(Mansur et al., 2025)
4	H ₂ SO ₄	Sulfonation reactor	100 °C; 3 h	Process can be modeled and integrated into continuous process design	Corrosive acidic medium and requires downstream neutralization	(Charoentanaworakun, Assabumrungrat, et al., 2023)
5	HSO ₃ Cl	Stirred batch reactor	800 rpm; 20 min pre-reaction in ice bath; 30 min after ME addition; 65 °C	High sulfonation reactivity	Highly corrosive and strongly exothermic reagent system	(Elsamani et al., 2025)

Continuous SO₃-based sulfonation, particularly in falling-film and thin-film reactors, provides high active matter, low di-salt formation, and efficient heat transfer because of rapid gas-liquid contact and short residence times, making it suitable for industrial production (Beghetto, 2025). However, this process requires strict control of FAME purity, moisture content, and operating conditions to maintain reaction selectivity (Siwayanan et al., 2021). In contrast, NaHSO₃-based batch sulfonation is simpler and more practical for laboratory-scale production, although longer reaction times and higher temperatures increase the risk of secondary reactions and lower product quality (Yusuff et al., 2023). Microwave-assisted sulfonation reduces processing time but its scalability and temperature uniformity remain limited (Qadariyah et al., 2024). Therefore, technology selection should consider MES quality, process efficiency, and the intended production scale.

The selection of sulfonation technology also determines the balance between conversion, selectivity, and downstream purification requirements. Excessive reaction severity can promote

the formation of di-salt and other undesired by-products, which may decrease active matter and adversely affect surfactant performance. Conversely, insufficient reaction severity may result in incomplete sulfonation and residual unsulfonated methyl esters. Therefore, MES production should be optimized by considering multiple quality indicators, including active matter, acid value, degree of sulfonation, di-salt content, color, and thermal stability, rather than using conversion alone. Such a multidimensional evaluation is particularly important when MES is intended for EOR applications, where surfactant stability and compatibility with reservoir conditions are critical.

MES Performance for Enhanced Oil Recovery

Table 4 shows that MES quality strongly influences EOR performance through interfacial tension (IFT) reduction, stability, and oil recovery efficiency. Despite the fact that direct EOR studies using WCO-derived MES remain limited, Table 4 includes both WCO-derived MES and closely related MES or green sulfonate systems as comparative benchmarks. These data should therefore be interpreted as indicative of MES-based EOR performance rather than as direct evidence exclusively for WCO-derived MES.

Table 4. Reported EOR Performance of Selected MES-Based Surfactant Systems

No	Reference	Surfactant system	Concentration	Reservoir conditions*	Lowest IFT (mN/m)	Incremental oil recovery (% OOIP)
1	(Leng et al., 2025)	MES/AEO-3 compound microemulsion	0.20 wt%	Low-permeability core	$\sim 10^{-2}$	25.61
2	(Kesarwani et al., 2022)	Flaxseed-oil-derived MES	0.70 wt%	Sand-pack flooding	0.25	48
3	(Charoentanaworakun, Srisuriyachai, et al., 2023)	Palm-oil-derived C16–C18 MES	0.2–0.85 wt%	Berea sandstone; saline conditions	1.72	53.1–57.6
4	(Ridaliani et al., 2025)	Palm oil-methyl ester sulfonate (MES)	1.5 wt%	Synthetic brine, laboratory core flooding	~ 0.455	68.8
5	(Hakiki et al., 2026)	C16 MES	2 mM	High-salinity formation water	0.02	~ 28

* Direct comparison of oil recovery values among these studies should be made cautiously because the surfactant formulations, concentrations, porous media, brine compositions, and flooding procedures differ considerably.

Reported MES-based formulations can substantially reduce oil–water IFT and provide significant incremental oil recovery under suitable conditions. However, the magnitude of these effects varies considerably with surfactant formulation, concentration, brine composition, rock properties, and other experimental conditions. Lower IFT increases the capillary number, improving the mobilization of residual oil trapped in porous media, although recovery also depends on surfactant stability and compatibility with reservoir brine (Yavrukova et al., 2024). MES–alkali formulations generally achieve higher oil recovery because alkali enhances interfacial activity and supports more efficient displacement (Deshmukh & Pathan, 2025). In addition, green sulfonate surfactants exhibit good thermal stability and salinity tolerance, making them suitable for chemical EOR applications in high-salinity reservoirs (Mushtaq et al., 2023). Overall, EOR performance depends not only on MES concentration but also on formulation stability and reservoir conditions.

The mechanism of MES-assisted oil recovery is not limited to IFT reduction. Surfactant adsorption onto the rock surface can modify rock wettability, potentially shifting the system toward a more water-wet condition and improving the displacement of trapped oil. At the same time, excessive adsorption can reduce the effective surfactant concentration in the aqueous phase and increase chemical consumption. Reservoir salinity and temperature further influence micelle formation, surfactant retention, and phase behavior. Consequently, an MES formulation that produces ultra-low IFT under laboratory conditions may not necessarily provide the highest oil recovery in an actual reservoir. Evaluating IFT together with wettability alteration, adsorption, phase behavior, and surfactant stability therefore provides a more reliable assessment of MES suitability for chemical EOR.

FINDINGS AND DISCUSSIONS

The findings from the reviewed literature indicate that WCO-derived MES should be evaluated as an integrated feedstock-process-property-performance system rather than through isolated processing stages (Figure 2). Variations in WCO quality can propagate through FAME production and sulfonation, eventually influencing MES characteristics and reservoir performance. The important implication is that optimization at one stage does not necessarily translate into improved performance at the next stage.

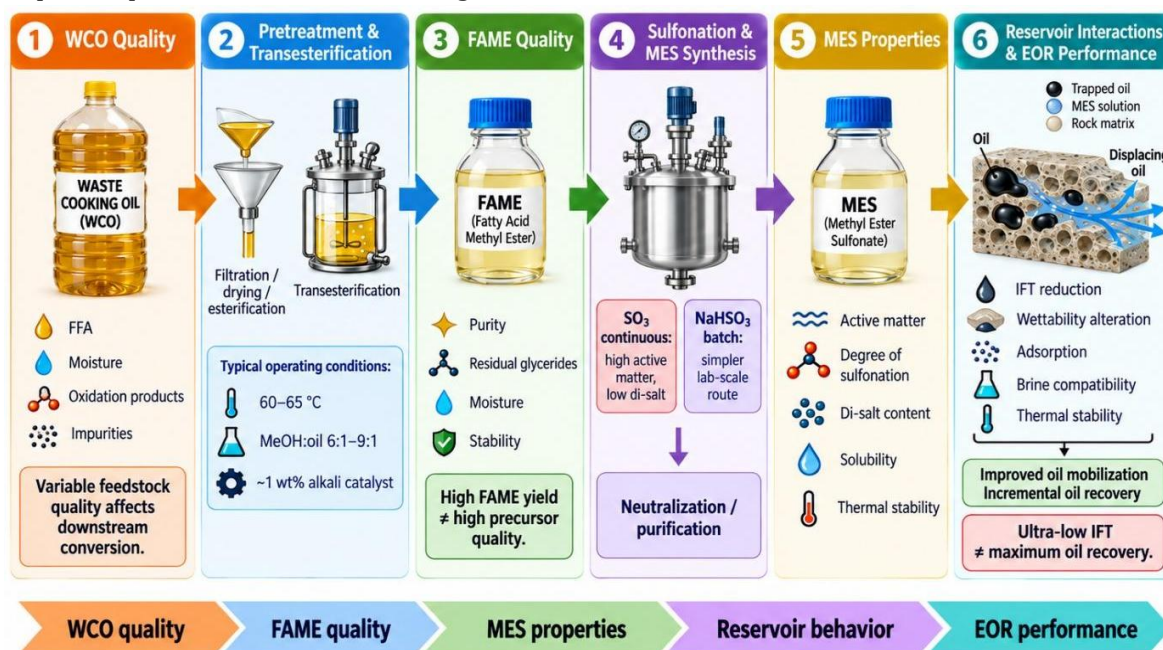


Figure 2. Feedstock-Process-Property-Performance Framework of WCO-derived MES for Enhanced Oil Recovery

For example, a high FAME yield alone does not ensure that the resulting material is an ideal precursor for MES synthesis. Residual glycerides, moisture, soaps, or degradation products may still influence sulfonation and final surfactant quality. Likewise, maximizing sulfonation conversion does not necessarily produce the most effective EOR surfactant if active matter, by-product formation, solubility, or stability are unfavorable. Thus, precursor and product quality should be considered alongside process conversion or yield.

The same principle applies to EOR evaluation. Although interfacial tension reduction is an important indicator of surfactant performance, ultra-low IFT alone does not guarantee maximum oil recovery. Adsorption, wettability alteration, brine compatibility, thermal stability, and other reservoir-related interactions may also influence the effective performance of MES. Therefore, the

final performance of WCO-derived MES depends on the combined effects of feedstock quality, synthesis conditions, surfactant properties, and reservoir conditions rather than on a single optimization parameter.

A major gap identified from the reviewed studies is the limited quantitative evidence connecting these stages within a single experimental framework. Most studies investigate WCO-to-FAME conversion, MES synthesis, or EOR performance separately, making it difficult to determine how changes in initial WCO characteristics ultimately affect oil recovery. Future studies should therefore integrate standardized WCO characterization, FAME quality assessment, MES physicochemical characterization, and reservoir-relevant testing. Such an approach would provide a stronger basis for establishing quantitative feedstock–process–property–performance relationships and for identifying the variables that most strongly govern the practical performance of WCO-derived MES.

RESEARCH LIMITATIONS

This review is limited by the small number of studies directly linking the complete WCO–FAME–MES–EOR pathway. In addition, differences in surfactant formulation, reservoir conditions, and experimental procedures limit direct comparison among reported EOR performances. Therefore, the findings should be interpreted primarily as integrated trends and research gaps that require validation through standardized experimental studies.

CONCLUSIONS AND FUTURE PERSPECTIVE

Waste cooking oil-derived methyl ester sulfonate offers a potential route for integrating waste valorization with chemical enhanced oil recovery. This review highlights that its performance should be evaluated across the complete WCO–FAME–MES–EOR pathway rather than through isolated optimization of individual stages. High FAME yield does not necessarily indicate suitable precursor quality, while high sulfonation conversion or low interfacial tension alone does not ensure optimal EOR performance. Future research should therefore establish quantitative relationships among WCO characteristics, FAME quality, MES physicochemical properties, and reservoir response within a consistent experimental framework.

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