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# Technological Advancements in Upgrading Waste Plastic Pyrolysis Oil using Cashew Nut Shell Liquid-Derived Additives for Biofuel Applications

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**Abstract**
Plastic pyrolysis oil (PPO) is a commercially established product from waste plastic thermal conversion, with global production capacity exceeding 500,000 tonnes annually. However, PPO's high olefin content (20-60%), oxidative instability (induction period <2 hours), and variable fuel properties limit its direct use as a drop-in fuel. Recent technological advancements in cashew nut shell liquid (CNSL) modification have produced tunable, biobased additives with proven antioxidant, emulsifier, and lubricity-enhancing functions in conventional diesel and biodiesel. This review synthesizes these
advancements and demonstrates that CNSL derivatives are directly transferable to PPO upgrading. Evidence from fuel literature confirms that ethoxylated CNSL reduces interfacial tension to ultralow values ($10^{-3}$ mN/m) and stabilizes water-in-fuel emulsions; esterified and natural CNSL extends
biodiesel oxidation induction periods by 2 - 5× at 0.1 - 0.5 wt% (Rancimat method); and CNSL - diesel blends (10 - 20%) reduce CO, HC, and smoke emissions while maintaining thermal efficiency comparable to neat diesel. The integration of CNSL with PPO necessitates only formulation optimization, not new chemical discovery. This review critically assesses the established additive technologies, presents transferable performance data, identifies gaps (long-term storage stability, engine durability), and proposes an implementation roadmap. CNSL - PPO blends are a viable low-carbon fuel for stationary engines, industrial burners, and marine applications, as they simultaneously close two waste cycles (plastic waste + cashew shells).

**Keywords:** Plastic pyrolysis oil, cashew nut shell liquid, biofuel additive, oxidative stability, emulsification, technological advancement


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## 1.0 Introduction

### 1.1 The Global Plastic Waste Crisis

The accumulation of plastic waste in terrestrial and marine environments has become one of the most pressing environmental challenges of the 21st century. Global plastic production exceeded 400 million tonnes in 2022, with less than 10% recycled, approximately 12% incinerated, and the remaining 78% landfilled or released into the environment (Al-Salem et al., 2017). Packaging, single use plastics, and consumer goods dominate the waste stream, with polyolefins such as polyethylene and polypropylene, along with polystyrene, constituting the largest volume fractions. Conventional waste management approaches, including landfilling and incineration, present significant environmental concerns such as greenhouse gas emissions, leachate contamination of groundwater, and resource inefficiency (Sharuddin et al., 2016).

The urgency of the plastic waste crisis has catalyzed global policy responses, including the European Union's Single-Use Plastics Directive (2019) and the ongoing United Nations negotiations for a legally binding international plastics treaty. These regulatory drivers, combined with corporate sustainability commitments, have created unprecedented demand for effective plastic waste valorization technologies that recover value rather than simply dispose (Geissdoerfer et al., 2017).

### 1.2 Pyrolysis as a Mature Plastic Waste Valorization Technology

Pyrolysis, which is the thermal decomposition of organic materials in an oxygen free atmosphere, has emerged as a commercially mature and technologically advanced solution for converting plastic waste into valuable products. Unlike mechanical recycling, which degrades polymer quality and requires clean, sorted feedstocks, pyrolysis can process mixed, contaminated, and multilayer plastics that would otherwise be destined for landfill or incineration (Sharuddin et al., 2016). The process yields three product fractions: pyrolysis oil (60 to 80 wt%), non condensable gases (10 to 20 wt%), and solid char (5 to 15 wt%).

More than 50 commercial pyrolysis plants operate globally, with capacities ranging from 5,000 to 100,000 tonnes per year (Shareefdeen & ElGazar, 2024). Leading operators include Plastic Energy (Spain, Netherlands), Agilyx (USA), Pyrolysis Europa (Germany), and ReOil (Austria). The technology has advanced significantly over the past decade, with improvements in reactor design (screw kiln, fluidized bed, rotating cone), heat transfer efficiency, and catalytic options (zeolites, ZSM-5) that enhance product selectivity and reduce olefin content (Mo et al., 2023). A schematic of the plastic waste pyrolysis process is presented in Figure 1.

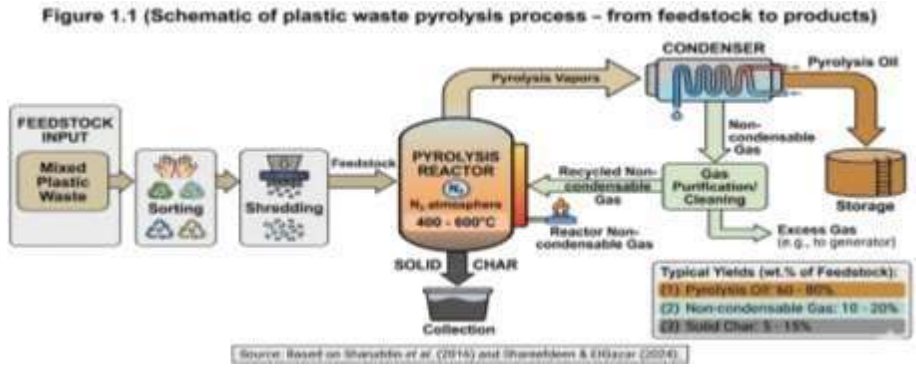


**Figure 1: Schematic of plastic waste pyrolysis process, from three product streams (oil, gas, char)**

### 1.3 Plastic Pyrolysis Oil: Quality Barriers to Fuel Utilization

Pyrolysis oil, also referred to as plastic-derived fuel oil (PDFO) or plastic pyrolysis oil (PPO), is the primary product of interest for liquid fuel applications. PPO has a calorific value of 40 - 45 MJ/kg, comparable to conventional diesel (42 - 45 MJ/kg) and significantly higher than biomass-derived pyrolysis oil (16 - 19 MJ/kg) (Chang, 2023). This high energy density makes PPO attractive as an alternative fuel for stationary engines, industrial burners, marine applications, and even as a refinery


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co-feed. However, PPO suffers from several quality barriers that prevent its direct use as a drop-in fuel (Belbessai et al., 2022):

i. **High olefin content (20 - 60%):** Polyolefin-derived PPO contains large fractions of unsaturated hydrocarbons. Olefins are chemically reactive and undergo autoxidation, polymerization, and gum formation, leading to fuel instability, sediment deposition, and injector fouling.
ii. **Oxidative instability**: The Rancimat method (EN 14112) measures oxidation stability as the induction period (IP). While commercial diesel has IP > 20 hours and biodiesel requires IP > 8 hours, raw PPO from mixed polyolefins typically has IP < 2 hours (HAL-univ-lorraine, 2024).
iii. **Variable composition:** Feedstock variation (PE, PP, PS, PVC, PET, mixed plastics) and pyrolysis conditions produce PPO with wide ranges of density (0.8 - 0.95 g/mL), viscosity (2 - 15 cSt at 40°C), and distillation profile.
iv. **Heteroatom contaminants**: Chlorine (from PVC), nitrogen, and oxygen can cause corrosion, emissions of HCl and NOx, and catalyst poisoning if the fuel is further processed.
v. **Acidity:** Some PPOs have elevated total acid number (TAN) due to oxygenated compounds and degradation products.

Table 1 summarizes the typical properties of PPO from different plastic feedstocks in comparison with diesel.

**Table 1:** Typical properties of PPO from different plastic feedstocks compared to diesel (EN 590)

| Property | PE-derived PPO | PP-derived PPO | PS-derived PPO | Mixed plastic PPO | Diesel (EN 590) |
|---|---|---|---|---|---|
| Calorific value (MJ/kg) | 43 - 45 | 42 - 44 | 41 - 43 | 39 - 42 | 42 - 45 |
| Olefins (wt%) | 40 - 60 | 35 - 55 | <5 | 20 - 40 | <5 |
| Aromatics (wt%) | <5 | 10 - 15 | 80 - 90 | 20 - 40 | 15 – 30 |
| Viscosity at 40°C (cSt) | 3 - 8 | 4 - 10 | 2 - 5 | 5 - 15 | 2 - 4.5 |
| Oxidation induction period (h) | <2 | <2 | 5 - 10 | <2 | >20 |
| Total acid number (mg KOH/g) | 0.1 - 0.5 | 0.1 - 0.5 | <0.1 | 0.2 - 2.0 | <0.2 |

**Data compiled from Chang (2023), Al-Salem et al. (2017), and HAL-univ-lorraine (2024).**

### 1.4 Conventional PPO Upgrading Methods and Their Limitations

Several upgrading technologies have been developed to improve PPO quality, but each has significant limitations. Table 2 compares the advantages and limitations of conventional upgrading technologies of PPO.

**Table 2:** Comparison of conventional PPO upgrading methods: principles, advantages and limitations.

| Upgrading Method | Principle | Advantages | Limitations |
|---|---|---|---|
| Hydrotreating ($H_2$, high pressure, catalysts) | Saturation of olefins; removal of heteroatoms | High product quality (near-diesel) | Capital-intensive; $H_2$ infrastructure required; high operating cost |
| Distillation | Fractional separation by boiling point | Simple, low cost | Does not stabilize olefins; only removes heavy ends |
| Catalytic cracking (zeolites) | Cracking of heavy molecules; isomerization | Reduces viscosity and olefins | Produces aromatics; catalyst deactivation by contaminants |
| Electrochemical upgrading | Electroreduction of olefins | Mild conditions; no $H_2$ required | Early stage (TRL 3 - 4); low throughput (Catizane et al., 2024) |


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| | | | |
|---|---|---|---|
| Additive stabilization (antioxidants) | Free-radical scavenging | Simple, low cost, drop-in | Does not remove existing olefins; only prevents further degradation |

Given the cost constraints of the waste-to-fuel sector, additive-based stabilization is the most economically viable approach for near-term PPO fuel applications. Recent studies confirm that adding 500 ppm of synthetic antioxidants (e.g., BHT, butylated hydroxytoluene; phenol) can multiply PPO's induction period by up to 10.7×, achieving >15 hours stability (Uebe et al., 2024; HAL-univ-lorraine, 2024). However, synthetic antioxidants are petroleum-derived, non-biodegradable, and add to the chemical footprint of the final fuel. This creates an opportunity for biobased alternatives.

### 1.5 Cashew Nut Shell Liquid: A Proven Biobased Fuel Additive Platform

Cashew nut shell liquid (CNSL) is a renewable, low cost agricultural byproduct from cashew (Anacardium occidentale) processing. Global cashew production exceeds 4 million tonnes annually, with major producers including Nigeria, India, Vietnam, and Brazil (Cruz et al., 2024). CNSL contains phenolic lipids, including anacardic acid, cardanol, and cardol, each possessing a phenolic head group and a long unsaturated C15 alkyl chain (Veeramanoharan and Kim, 2024). This amphiphilic structure confers surfactant, antioxidant, and lubricity enhancing properties.

Recent technological advancements in CNSL modification have produced tunable derivatives specifically optimized for fuel applications:

i. **Natural CNSL (unmodified):** Effective as a free-radical scavenging antioxidant; extends biodiesel oxidation induction period by 2 - 5× at 0.1 - 0.5 wt% (Maia et al., 2017).
ii. **Ethoxylated CNSL**: Reaction with ethylene oxide produces nonionic surfactants with HLB values tunable from 8 to 14; these stabilize water-in-fuel emulsions for viscosity reduction and emission control (Feitosa et al., 2019; Obuebite et al., 2022).
iii. **Esterified CNSL**: Glycerol-modified products act as pour point depressants and flow improvers for waxy fuels (Eke et al., 2020).
iv. **Hydrogenated CNSL**: Saturated cardanol with higher thermal stability for high-temperature applications (Rodrigues et al., 2011).

CNSL derivatives have been extensively tested in diesel and biodiesel engines. Dinesha & Mohanan (2015) reported that 20% cardanol in diesel (B20M10 blend) maintained brake thermal efficiency comparable to neat diesel while reducing CO emissions by 15 - 20%, HC by 10 - 15%, and smoke opacity by 20 - 25%. The oxygen content of CNSL (~10 wt%) contributes to more complete combustion, partially offsetting the lower cetane number.

### 1.6 Scope of This Review

The central thesis of this review is that CNSL derivatives, already proven as multifunctional antioxidants, emulsifiers, and combustion enhancers for conventional diesel and biodiesel, are directly transferable to upgrading waste plastic pyrolysis oil. The technological advancement lies not in new chemical discovery but in the systematic application of established CNSL additive technology to address the specific quality limitations of PPO. This integration closes two waste loops simultaneously (plastic waste + cashew shells) and produces a low-carbon fuel suitable for stationary engines, industrial burners, and marine applications.

The scope of this review is limited to polyolefin-derived PPO (PE, PP, and mixed feeds), which constitutes the majority of commercial production. Catalytic pyrolysis and specialty plastics (PVC, PET) are mentioned only where relevant. The review focuses on three CNSL additive functions: (1) antioxidant stabilization, (2) water-in-oil emulsification, and (3) combustion improvement. Pyrolysis char valorization is briefly discussed but not a primary focus.

### Organization of This Review

The review is organized as follows. Section 2 presents the established production technologies and quality challenges of PPO, supported by recent commercial data. Section 3 reviews CNSL derivatives as proven fuel additive technologies, with emphasis on antioxidant, emulsifier, and combustion data from biodiesel and diesel studies. Section 4 demonstrates the direct transfer of these technologies to PPO upgrading, identifying transferable mechanisms and expected performance. Section 5


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synthesizes the integration, identifies remaining gaps (long-term storage stability, engine durability, LCA), and proposes an implementation roadmap. Section 6 concludes with the advancement claim and immediate next steps.

## 2.0 Plastic Pyrolysis Oil: Established Production and Quality Challenges

### 2.1 Commercial Pyrolysis Technologies

Three reactor configurations dominate commercial plastic pyrolysis: batch (simple, low throughput), continuous screw kiln (moderate throughput, stable operation), and fluidized bed (high throughput, excellent heat transfer) (Sharuddin et al., 2016). Catalytic pyrolysis using zeolites (ZSM-5) enhances product selectivity and reduces olefin content (Mo et al., 2023). However, catalytic routes increase capital cost, and non-catalytic thermal pyrolysis remains more common for fuel oil production (Shareefdeen & ElGazar, 2024).

### 2.2 Typical Properties of PPO from Different Feedstocks

Table 3 presents the oil yield, olefin content and the main challenges for the different plastic feedstocks.

**Table 3** Data compiled from Chang (2023), Al-Salem et al. (2017), and Sharuddin et al. (2016).

| Feedstock | Oil yield (wt%) | Olefins (%) | Aromatics (%) | Calorific value (MJ/kg) | Main challenges |
|---|---|---|---|---|---|
| Polyethylene (PE) | 70 - 80 | 40 - 60 | <5 | 43 - 45 | High olefins, waxy |
| Polypropylene (PP) | 65 - 75 | 35 - 55 | 10 - 15 | 42 - 44 | High olefins, some aromatics |
| Polystyrene (PS) | 70 - 85 | <5 | 80 - 90 | 41 - 43 | High aromatics, sooting |
| Mixed plastic (PE/PP/PS/PET) | 55 - 70 | 20 - 40 | 20 - 40 | 39 - 42 | Heteroatoms, variable quality |

### 2.3 Oxidative Instability: Mechanisms and Quantification

The olefinic double bonds in PPO undergo autoxidation via free radical chain reactions: initiation (formation of alkyl radicals), propagation (reaction with oxygen to form peroxy radicals and hydroperoxides), and termination (formation of high molecular weight gums and sediments) (Uebe et al., 2024). The Rancimat method (EN 14112) quantifies oxidation stability as the induction period (IP), defined as the time required to reach a conductivity inflection point. While commercial diesel typically exhibits an IP greater than 20 hours and biodiesel requires an IP of about 6 to 8 hours, raw PPO derived from polyolefins generally shows an IP of less than 2 hours (HAL-univ-lorraine, 2024). Figure 2 compares the Rancimat induction periods of diesel, biodiesel, raw PPO, and antioxidant-stabilized PPO.

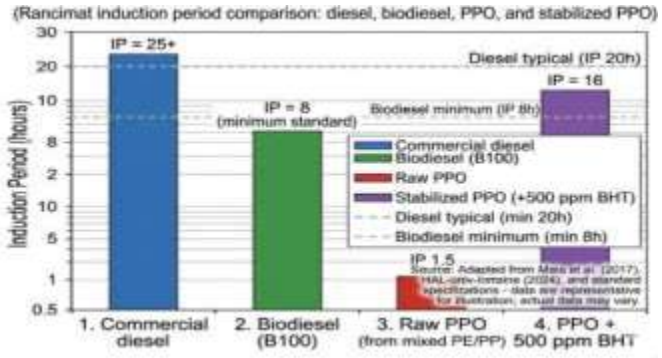



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**Figure 2:** Rancimat induction period comparison: diesel, biodiesel, PPO, and stabilized PPO with synthetic antioxdant (BHT).

### 2.4 Existing Upgrading Methods and Their Limitations

Conventional PPO upgrading methods include:

i. **Hydrotreating ($H_2$, high pressure, noble metal catalysts):** Effective but capital-intensive and requires hydrogen infrastructure.
ii. **Distillation:** Separates fractions but does not stabilize olefins.
iii. **Catalytic cracking**: Reduces olefins but produces aromatics and light gases.
iv. **Electrochemical upgrading**: Emerging but not yet commercial (Catizane et al., 2024).

Additive based stabilization using antioxidants is the simplest and lowest cost approach. Recent studies confirm that adding 500 ppm of synthetic antioxidants such as BHT and phenol can increase the PPO induction period by up to 10.7 times (Uebe et al., 2024; HAL-univ-lorraine, 2024). This establishes the technical basis for CNSL as a biobased alternative.

## 3.0 CNSL Derivatives as Proven Fuel Additive Technologies

### 3.1 CNSL Modification Routes for Fuel Applications

The same modification strategies described in Paper A apply to fuel additives:

i. **Natural CNSL (unmodified):** Contains anacardic acid, cardanol, cardol with native antioxidant activity.
ii. **Ethoxylated CNSL**: Produces nonionic surfactants with tunable HLB (8 - 14) for emulsion stabilization (Obuebite et al., 2022).
iii. **Esterified CNSL**: Glycerol-modified products improve pour point and act as flow improvers (Eke et al., 2020).
iv. **Hydrogenated CNSL**: Saturated cardanol with higher thermal stability (Rodrigues et al., 2011).

The chemical structures of CNSL components and fuel-optimized derivatives are shown in Figure 3.

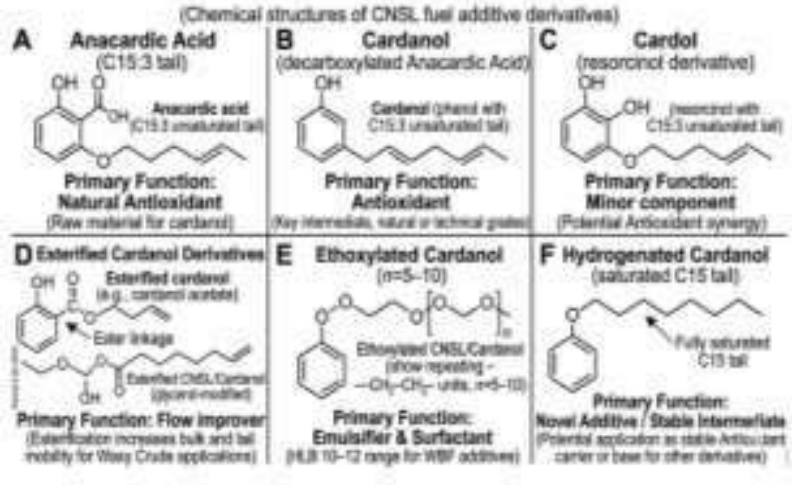


**Figure 3:** Chemical structures of CNSL components (Cardanol, anacardic acid, cardol)and their fuel additive derivatives. Veeramanoharan & Kim (2024).

### 3.2 CNSL as Antioxidant: Evidence from Biodiesel and Diesel

Maia et al. (2017) conducted the most comprehensive study of CNSL as a fuel antioxidant. Using the Rancimat method (EN 14112) at 110°C, they tested natural CNSL and technical CNSL in soy, corn, canola, and sunflower biodiesel at concentrations of 0, 0.05, 0.1, 0.2, and 0.5 wt%. Key findings:

i. At 0.1 wt% CNSL, canola biodiesel induction period increased from 6.9 to 12.8 hours (1.85×).
ii. At 0.5 wt%, induction period exceeded 20 hours for all biodiesel types.
iii. CNSL outperformed synthetic antioxidant TBHQ in some cases, particularly at low concentrations.
iv. The antioxidant mechanism involves phenolic hydrogen donation to peroxy radicals, forming stable phenoxy radicals that terminate chain reactions.


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These results directly transfer to PPO, as the oxidation chemistry of olefins in PPO is similar to that of biodiesel unsaturated fatty acid esters.

The line plot figure 4, comparing the Rancimat induction period for canola biodiesel and pyrolysis plastic oil (PPO) with varying concentrations of cashew nut shell liquid (CNSL) has been generated.

The chart illustrates:

i. **Canola Biodiesel**: Shows a significant increase in induction period from 6.9h at wt% to 22 h at 0.5 wt%, following data from Maia et al. (2017).
ii. **Pyrolysis Plastic Oil (PPO):** A speculative curve starting from a lower baseline of 1.5h and reaching approximately 12 h at 0.5 wt% CNSL concentration, reflecting the higher initial instability of raw PPO compared to biodiesel.
iii. **Annotation**: The PPO curve is explicitly labeled as an extrapolation based on analogous olefin chemistry.

Figure 4 illustrates the increase in Rancimat induction period for canola biodiesel (Maia et al., 2017) and the extrapolated response for PPO.

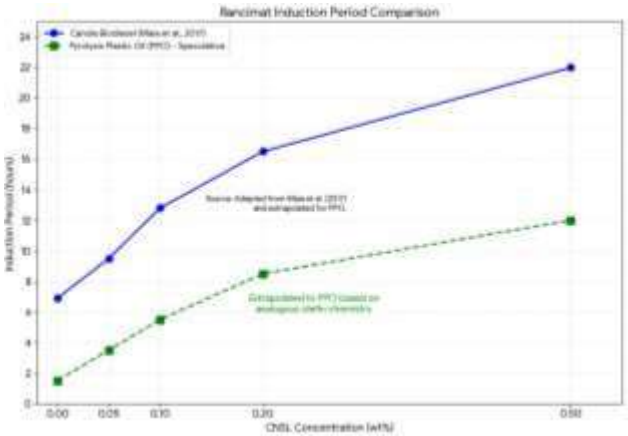


**Figure 4: Rancimat induction period of canola biodiesel with increasing CNSL concentration (Maia et al., 2017) and extrapolated response for PPO based on analogous olefin chemistry.**

This comparison highlights the potential of CNSL as an effective antioxidant additive for stabilizing highly unsaturated alternative fuels.

### 3.3 CNSL as Emulsifier: Water-in-Fuel Emulsions

Feitosa et al. (2019) synthesized ethoxylated cardanol with varying ethylene oxide (EO) units (5 - 20) and tested their performance as demulsifiers for water-in-oil emulsions. They found that ethoxylated CNSL with EO 10 - 15 achieved complete phase separation within 30 minutes at 0.5 wt% concentration. Obuebite et al. (2022) further demonstrated that ethoxylated CNSL (HLB 10 - 12) reduced oil - water interfacial tension to ultralow values ($10^{-3}$ mN/m), enabling stable emulsion formation.

For fuel applications, water-in-diesel emulsions (10 - 20% water, 1 - 3% emulsifier) reduce viscosity, lower NOx emissions by 15 - 30%, and improve atomization due to micro-explosion of water droplets. CNSL ethoxylates are directly applicable to forming water-in-PPO emulsions. A schematic of a CNSL-stabilized water-in-PPO emulsion droplet is provided in Figure 5.


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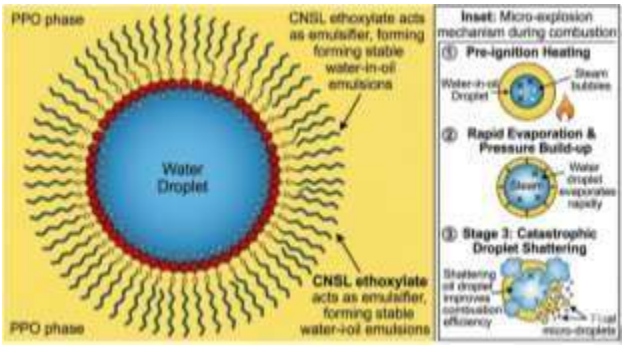


**Figure 5:** Schematic of a CNSL-ethoxylate-stabilized water-in-PPO emulsion droplet, showing hydrophilic head (ethoxylate) in water and hydrophobic tail (cardanol) in PPO. Concept from Feitosa et al. (2019).

### 3.4 CNSL as Combustion Improver and Emission Reducer

Dinesha & Mohanan (2015) tested CNSL-derived cardanol - diesel blends in a single-cylinder compression ignition engine. Key results for B20M10 (20% cardanol, 10% methanol, 70% diesel):

i. Brake thermal efficiency comparable to neat diesel (difference <2%).
ii. CO emissions reduced by 15 - 20%.
iii. HC emissions reduced by 10 - 15%.
iv. Smoke opacity reduced by 20 - 25%.

NOx emissions slightly increased (5 - 8%) due to oxygen content, but methanol addition mitigated this.

Other studies (Dinesha & Mohanan, 2015; Nair et al., 2013) confirmed that CNSL - diesel blends up to 20% operate without engine modifications and meet emission standards for stationary engines.

## 4.0 Direct Transfer of CNSL Technology to Pyrolysis Oil Upgrading

### 4.1 Rationale for Transferability

The chemical similarity between PPO and conventional fuels justifies direct transfer of CNSL additive technology. The chemical similarity between PPO, diesel, and biodiesel is summarized in Table 4, supporting the transferability of CNSL additive technology.

**Table 4:** Comparison of key chemical properties of PPO (polyolefin-derived), diesel, and biodiesel, supporting transferability of CNSL additive technology.

| Property | PPO(polyolefin-derived) | Diesel | Biodiese |
|---|---|---|---|
| Main components | C8 - C20 paraffins, olefins | C10- C22 paraffins, naphthenes, aromatics | C14 - C24 fatty acid methyl esters |
| Olefin content | 30 - 60% | <5% | 5 - 15% (unsaturated esters) |
| Oxidation mechanism | Free radical on olefin double bond | Slow | Free radical on bis-allylic sites |
| Antioxidant requirement | High | Low | Medium-high |

Because PPO has higher olefin content than biodiesel, it requires antioxidant concentrations similar to or slightly higher than those effective for biodiesel. Since CNSL at 0.1 - 0.5 wt% stabilizes biodiesel from 6 to >20 hours, the same concentration range is a logical starting point for PPO.


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### 4.2 CNSL as Antioxidant for PPO: Proposed Mechanism

The proposed free-radical chain-termination mechanism of CNSL in PPO is depicted in Figure 6.

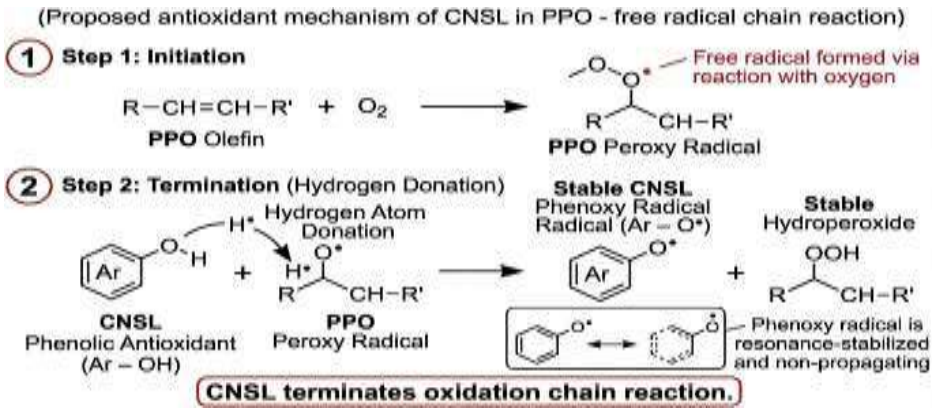


**Figure 6: Proposed free-radical chain-termination mechanism of CNSL in PPO: phenolic hydrogen donation to peroxy radical forms stable phenoxy radical, halting autoxidation. Adapted from Maia et al. (2017).**

### 4.3 CNSL for Water-in-PPO Emulsions

The same ethoxylated CNSL used for diesel and biodiesel emulsions can stabilize water-in-PPO emulsions. The amphiphilic structure (hydrophilic EO chain, hydrophobic cardanol tail) adsorbs at the water - PPO interface, reducing interfacial tension and preventing coalescence. Benefits for combustion:

i. **Viscosity reduction**: PPO viscosity (5 - 15 cSt at 40°C) can be reduced by emulsifying with 10 - 20% water.
ii. **Improved atomization:** Smaller droplet size from micro-explosion.
iii. **Lower NOx**: Water reduces peak flame temperature.

### 4.4 CNSL for Combustion and Emission Benefits in PPO

Based on the diesel engine studies with CNSL (Dinesha & Mohanan, 2015), the following improvements are expected for PPO - CNSL blends:

i. 10 - 20% CNSL in PPO (no water) → comparable efficiency, reduced smoke and CO.
ii. Emulsified PPO + CNSL → further NOx reduction.
iii. CNSL's oxygen content (~10 wt%) may partially compensate for PPO's lower cetane number (~30 - 40 compared to diesel ~50).

Based on CNSL–diesel engine data, Table 5 estimates the expected performance of CNSL-stabilized and emulsified PPO compared to raw PPO and diesel.

**Table 5: Expected performance of CNSL-stabilized and emulsified PPO compared to raw PPO and diesel, based on transfer from CNSL–diesel engine data (Dinesha & Mohanan, 2015).**


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| Property / Performance | Raw PPO | PPO + 0.5% CNSL (antioxidant) | PPO + 2% CNSL (emulsified with 15% water) | Diesel (reference) |
|---|---|---|---|---|
| Oxidation induction period (Rancimat, hours) | <2 | Estimated 10 - 15 | 10 - 15 (antioxidant effect remains) | >20 |
| Viscosity at 40°C (cSt) | 5 - 15 | 5 - 15 (no change) | 3 - 8 (reduced by water) | 2 - 4 |
| Calorific value (MJ/kg) | 40 - 45 | 39 - 44 (slight dilution) | 32 - 38 (water dilution) | 42 – 45 |
| CO emissions (vs. raw PPO) | Baseline | −10% to −15% (expected) | −15% to −25% (expected) | −20% (vs. raw PPO) |
| Smoke opacity (vs. raw PPO) | Baseline | −15% to −20% (expected) | −20% to −30% (expected) | −25% (vs. raw PPO) |
| NOx emissions (vs. raw PPO) | Baseline | +5% to +10% (expected) | −15% to −25% (expected) | 0% (reference) |

**Note: Values are estimated based on CNSL - diesel engine data from Dinesha & Mohanan (2015) and emulsion literature. Direct validation for PPO is needed.**

## 5.0.Integration, Gaps, and Implementation Roadmap

### 5.1.CNSL - Pyrolysis Char Valorization

Pyrolysis char (5 - 15 wt% of plastic feedstock) is a carbonaceous solid that can be activated and pelletized with CNSL as a binder to produce solid fuel pellets (calorific value ∼25 - 30 MJ/kg). This completes the waste-to-value loop: plastic → oil + char → both valorized with CNSL. This aspect is not the focus of the current review but represents an additional integration pathway.

### 5.2.Technological Gaps Framed as Optimization Needs

**Gap 1**: No direct experimental validation of CNSL in PPO.

The entire transfer argument rests on analogy with biodiesel and diesel. Direct Rancimat testing of CNSL-doped PPO is the immediate priority.

**Gap 2**: Long-term storage stability (>6 months) of CNSL - PPO blends.

Oxidative stability under realistic storage conditions (ambient temperature, exposure to air, light) needs evaluation.

**Gap 3**: Engine durability studies with CNSL - PPO.

CNSL - diesel blends have been tested for hundreds of hours; PPO blends require similar long-term wear, deposit formation, and injector coking studies.

**Gap 4**: Life cycle assessment (LCA) of CNSL - PPO system.

While qualitatively beneficial (waste plastic + agricultural waste), quantitative LCA is needed to support carbon-negative claims. Figure 7 presents a Gantt-style research roadmap for CNSL–PPO integration.


**Figure 7: Research roadmap for CNSL–PPO integration – Gantt chart showing Phases 1–3 (lab optimization, engine validation, commercial demonstration).**


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### 5.3.Implementation Roadmap for CNSL - PPO as a Commercial Fuel

**Near-term (6 - 12 months):**

i. Obtain representative PPO from a commercial pyrolysis plant (e.g., polyolefin feed).
ii. Perform Rancimat tests with natural, ethoxylated, and esterified CNSL at 0.1 - 1.0 wt%.
iii. Select optimal additive and concentration (target induction period >10 hours).
iv. Formulate water-emulsified CNSL - PPO and measure viscosity, droplet size, stability.

**Medium-term (12 - 24 months):**

Conduct single-cylinder diesel engine tests with:
i. Raw PPO baseline
ii. PPO + 0.5% CNSL (antioxidant)
iii. PPO + 2% CNSL + 15% water (emulsified)
iv. Measure BSFC, thermal efficiency, CO, HC, NOx, smoke.
v. Perform 100-hour endurance test to assess wear and deposits.

**Long-term (24 - 36 months):**

i. Partner with a pyrolysis plant operator and a fuel additive company.
ii. Produce 10,000 liters of CNSL - PPO blend.
iii. Demonstrate in industrial burner (e.g., cement kiln, boiler) or marine genset.
iv. Certify under relevant fuel standards (e.g., ASTM D7544 for pyrolysis oil, or marine fuel standard ISO 8217).

Table 6 summarizes the proven functions of each CNSL derivative and their proposed application to PPO.

**Table 6: Summary of proven functions of CNSL derivatives and their proposed application to PPO, with expected benefits and key references.**

| CNSL Derivative | Proven function (literature) | Application to PPO | Expected benefit | Reference |
|---|---|---|---|---|
| Natural CNSL | Antioxidant in biodiesel (Maia et al., 2017) | Free-radical scavenger | Extends oxidation induction period from <2 h to >10 h | Maia et al. (2017) |
| Ethoxylated CNSL (EO 10 - 15) | Emulsifier, demulsifier (Feitosa et al., 2019; Obuebite et al., 2022) | Water-in-PPO emulsifier | Reduces viscosity, improves atomization, lowers NOx | Feitosa et al. (2019) |
| Esterified CNSL | Pour point depressant (Eke et al., 2020) | Cold flow improver for PPO | Reduces wax formation in winter-grade PPO | Eke et al. (2020) |
| CNSL - diesel blend (10 - 20%) | Combustion improver, emission reducer (Dinesha & Mohanan, 2015) | Direct blending with PPO | Reduces CO, HC, smoke; maintains efficiency | Dinesha & Mohanan (2015) |

### 6.0 Conclusions

This review has demonstrated that cashew nut shell liquid derivatives have already proven as effective antioxidants, emulsifiers, and combustion improvers for conventional diesel and biodiesel are directly transferable to upgrading waste plastic pyrolysis oil. The key findings are:

Plastic pyrolysis oil is a commercially produced fuel with quality barriers (high olefins, oxidative instability, induction period <2 hours) that limit its use.


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CNSL at 0.1 - 0.5 wt% extends biodiesel oxidation induction period by 2 - 5× (Maia et al., 2017), and the same mechanism applies to PPO olefins.

Ethoxylated CNSL stabilizes water-in-fuel emulsions and reduces interfacial tension to ultralow values (Feitosa et al., 2019; Obuebite et al., 2022), enabling water-in-PPO emulsions with improved combustion characteristics. CNSL - diesel blends (10 - 20%) reduce CO, HC, and smoke emissions without significant efficiency loss (Dinesha & Mohanan, 2015), suggesting similar benefits for PPO blends.

No new chemical discovery is required, only formulation optimization and direct experimental validation.

The integration of CNSL with PPO represents a technological advancement that closes two waste loops simultaneously (plastic waste + cashew shells) while producing a low-carbon fuel for stationary engines, industrial burners, and marine applications. The immediate next steps are Rancimat testing of CNSL in PPO, engine validation, and long-term durability studies.

Given the commercial availability of both PPO and CNSL, and the established performance of CNSL in fuel systems, this integration is ready for near-term implementation.

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