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EVALUATION OF BIOSYNTHETIC BLENDS BASED ON POLYOL ESTERS (POE) FOR ENVIRONMENTALLY FRIENDLY HYDRAULIC APPLICATIONS

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Abstract: *Increasing sustainability requirements in the lubricants sector have driven the shift from mineral bases to environmentally friendly bio-synthetic and ester bases. Ecological hydraulic oils must combine high biodegradability (>70%), oxidative stability and compatibility with elastomers and modern hydraulic systems (piston pumps, gear pumps). In the context of the transition to green and sustainable lubricants, blends of polyolesters (POE) with bio-derived esters such as TMP-esters, PE-esters, glycerol carbonate, modified phospholipids and epoxidized acylglycerides represent a promising direction for hydraulic applications with high requirements for stability, antiwear protection (AW) and EP performance. The need to reduce the ecological impact of hydraulic lubricants has led to the development of bio-synthetic bases (modified natural esters, polyol esters, glycerol carbonate, epoxidized lecithin, etc.), capable of combining high biodegradability with the tribological performance of synthetic POE (polyol ester) bases.*

Keywords: *Polyol esters (POE), modified lecithin (GPL), bio-derived esters (TMP), anti-wear protection (AW) and extreme pressure (EP) performance*

1. Introduction

The hydraulic fluids used to drive piston pumps have characteristics that enable them to work under technical conditions such as high pressures, thermal fluctuations, friction and wear stresses, demulsification requirements, compatibility with seals, etc.).

Formulations must meet requirements for viscosity, thermal stability, oxidation stability, pressure resistance, as well as foaming and demulsification properties – all of which are relevant conditions for hydraulic pumps.

Blends with polyol esters can offer:

- biodegradability and potential for reduced environmental impact;
- stability at extreme temperatures, due to the chemical structure of polyol esters (R-COO-R');
- resistance to hydrolysis, important in wet or high temperature hydraulic applications;
- good compatibility with internal materials (seal ring, gaskets, metals), depending on the esters used and the control of auxiliary properties.

2. Methods and Materials

Possibility to adjust properties through mixtures – combining different esters or esters with synthetic/mineral oils.

- ➢ the presence of the ester functional group (-COO-), confers a distinct polarity, significantly influencing the physical and chemical properties of the mixtures; (R is an acid radical and R' is an alcohol radical);
- ➢ esters can be classified into various categories:

- diesters (containing two ester groups);
- polyol esters (derived from alcohols with more than two hydroxyl groups);
- complex esters (which may also include other functional groups in their structure).

This structural diversity allows for fine-tuning of the properties of esters to meet the specific requirements of different lubrication applications [1], esters play a dual role being used as:

- base oils - which provide superior performance in applications with extreme temperatures or high loads;
- additives, being added in small quantities to optimize lubricant formulations based on mineral or synthetic oils (lubrication, antifoam, thermal stability) [2];

➢ esters are included in Group V, according to the American Petroleum Institute (API) which includes all base oils that do not fall into Groups I-IV classified according to the content of saturated groups and sulfur, as well as the viscosity index.

This classification helps to compare esters with other types of base oils in terms of manufacturing process, properties and typical applications [3].

Comparative analysis of esters with base oils from other API groups highlights their specific advantages, namely:

➢ superior thermal and oxidative stability (absence of hydrogen atoms in the beta position relative to the ester group e.g. neopolyol esters or Secondary Polyol Ester™ (SPE));

- contribute to extending the service life of the lubricant and reducing the formation of harmful deposits;
- have the ability to maintain performance at temperatures up to 220°C [4];

➢ low volatility - reduction of oil losses through evaporation [5];
➢ good solubility (e.g. polyalphaolefins (PAO)) - reduced deposit formation; keeping oxidation products in suspension, uniform distribution of additives;
➢ compatibility with other base oils and seals [6];
➢ adhesion to metal surfaces, (due to their polarity) - molecular film that lubricates, and protects against oxidation and corrosion under high pressure or extreme temperatures [7];
➢ biodegradability (ester derivatives) - reduce the impact on the environment in case of leakage [8], [9];
➢ can act as friction modifiers, (esters of dicarboxylic acids) reduce friction coefficients and wear under moderate load conditions;
➢ resistance to oxidative processes (e.g. polyol esters and polyalphaolefins (PAO)) [10];
➢ viscosity index and reduce the pour point of oils [11],
➢ hydrodynamic films stable at high temperatures and high shear rates [12].

Table 1: Comparative analysis with base oils from API groups

Property	**Group I**	**Group II**	**Group III**	**Group IV (PAO)**	**Group V (Esters)**
Saturated Solutions	<90%	≥90%	≥90%	Synthetic	Synthetic/Other
Sulfur	>0.03%	≤0.03%	≤0.03%	0%	Variable
Viscosity Index	80-120	80-120	>120	>120	Variable, good
Thermal Stability	Low	Average	High	Excellent	Superior
Oxidative Stability	Low	Average	High	Excellent	Good/Excellent
Biodegradability	Low	Low	Low	Low	Variable, good
Cost	Low	Average	Medium-High	High	Very high
Additive Solubility	Good	Good	Good	Limited	Good/Excellent
Seal Compatibility	Good	Good	Good	shrinkage	Swelling

- Group I contains less refined, lower cost, lower performance base oils containing more sulfur and aromatic groups [13];

- Group II contains slightly improved oils, but are not recommended for high performance applications [14];
- Group III includes high purity oils, sometimes considered synthetic, although they are derived from crude oil [15];
- Group IV (PAO) offers excellent stability at extreme temperatures, but has limited additive solubility, risk of seal shrinkage, and limited wear properties [16];
- Group V includes esters, polyglycols and silicones, offering superior thermal and oxidative stability, excellent lubricity and often biodegradability, have higher costs and possible seal compatibility issues [17];
  - ➢ fire safety (synthetic esters) -Alpha-Tech® technology developed by Pakelo-combines ester bases with Group IV (PAO) bases, are advanced formulations for high performance [18];
  - ➢ improve tribological properties (pentaerythritol esters + commercial oils) [19];

The literature indicates that the use of polyol esters (POE) in hydraulic oils offers advantages such as good thermal and oxidative stability, compatibility with a wide range of materials, and biodegradability. Although polyol esters are highly efficient and versatile, research is continuously aimed at finding solutions that combine performance with sustainability and low cost.

- ❖ Performance Improvement: researchers are looking for fluids with superior lubrication properties and stability at extreme temperatures to increase the life of hydraulic systems and their operating efficiency.
- ❖ Sustainability: there is a growing interest in biodegradable hydraulic fluids and products from renewable resources to reduce environmental impact.
- ❖ Costs: reducing production and maintenance costs by using economically competitive substitutes to be viable.

Table 2: Formulations of polyol ester mixtures, suitable or adaptable for gear pumps or piston pumps

Brevet / document	Formulations / important components	Properties/tests (temperature, viscosity, etc.)	Rating: Suitable for gear/piston pumps
EP 3172294 B1 / US9850444B2 („Unsaturated polyol esters used in hydraulic fluid applications”)	Unsaturated polyol esters. Polyols + unsaturated fatty acids are used	Use in hydraulic applications is mentioned, including pumps (gear, valves, piston). Requires oxidation stability, seal compatibility, wide operating temperatures.	Very promising. If the fluids meet the required viscosity and seal compatibility, they can be used in both gear and piston pumps.
Patent U.S. 6,361,711 („Flame retardant hydraulic oil containing a synthetic ester formed by reaction of a polyol … mixture of acids including oleic acid and isostearic acid”)	Polyols such as neopentyl glycol, glycerin, trimethylolpropane reacted with a combination of acids (oleic, isostearic, etc.).	Kinematic viscosity at 40 °C is specified between ~40-80 cSt; high flash point (≈ 290 °C). Good thermal stability. Oxidation resistance and flame-retardant properties.	Could be good for gear/piston pumps, especially where temperature and fire safety are important. However, the viscosity needs to be appropriate for the system.
U.S. Hydraulic fluids (UniChema Chemie B.V.) Pat. nr. 6,693,064	Fluid based almost entirely on mixed esters of polyols; short chain fatty acids (C5-C12) + long chain acids (C16-C22). Recommended polyol: Trimethylolpropane.	Emphasis is placed on low temperature properties: rheological stability after prolonged exposure to −30 °C; maximum permissible viscosity 7000 mm²/s (≈ cSt) in certain tests.	For gear or piston pumps in cold/high load environments, it could be suitable; but need to check the pour point and whether the fluid does not become too viscous at start-up.

Brevet / document	Formulations / important components	Properties/tests (temperature, viscosity, etc.)	Rating: Suitable for gear/piston pumps
US8299004B2 („Hydraulic fluid and hydraulic system”)	Blend containing base oil (mineral or synthetic), polyol esters, polyalcohol’s, plus other additives (viscosity index, modulators).	Fluid with high bulk modulus, viscosity index ≥ 110, pour point ≤ −25 °C; good compatibility is proposed.	Very suitable for high pressure pumps, especially piston pumps – where compressibility modulus, volumetric losses and low temperature control are critical.

To classify POE, POE/GC, POE/LPG, POE/AG-E, POE/TMP-E mixtures in wear areas (wet, high temperatures, intense loads), we must look at the hydrolytic, oxidative stability and lubricant film resistance.

❖ POE = polyol-ester — synthetic ester (base for lubricating oils) obtained by esterification of a polyol (e.g.: TMP, pentaerythritol, neopentyl glycol, etc.) with fatty acids:
- have good thermo-oxidative stability, high viscosity index and miscibility with hydrocarbons, which is why they are frequently used as oils for various systems and as technical lubricants.

❖ POE/TMP-E = trimethylolpropane (TMP) ester:
- form oils with good lubricating properties, hydraulic stability and good viscosity index;
- are used for industrial lubricants and fluids resistant to high temperatures;

❖ POE/GC- derivative based on glycerol carbonate / glycerol esters:
- give esters with eco-friendly characteristics (good biodegradability, polarity);
- tends to be more polar, with good ability to dissolve/transport moisture, useful in applications where miscibility and compatibility with polar fluids matter;

❖ POE/GPL-glycerol based on polyols or polyglycerol:
- glycerin esters (glycerol/polyglycerol) offer good lubricating properties, low pour point and stability;

❖ POE/AG-E- indicates an adipic ester or “alkyl-glycerol ester”:
- provides lower viscosity, good low temperature lubricity and chemical stability;
- can be used where low temperature flow and compatibility with certain systems are required (e.g. specialized applications).

Disadvantages and limitations of ester-based lubricants

❖ The high cost is significant; polyol esters are among the most expensive base oils, [20,21];

❖ Compatibility with sealing materials (e.g. polar esters can cause swelling [22,23].

Therefore the mixture is balanced with an API Group IV base (PAO), which has the opposite tendency (contraction), to maintain both flexibility and the original dimensions of the seals).

Formulations for hydraulic systems (mobile / industrial systems, anti-wear)

POE/TMP-E (TMP-ester) 85–92% — TMP ester base oil, blend with good viscosity index, thermo-oxidative stability and tribological properties suitable for high-pressure pumps and valves.

Additives: AW/EP (5–7%), antioxidant (phenolic + amine = 1–3%), corrosion inhibitor (0.5–1%), anti-foaming agent (0.2–0.5%), pour point depressant (0.1–1%).

Viscosity: ISO VG32–46 for mobile applications; VG46–100 for industrial systems at higher temperatures.

Hygroscopicity control: POEs are polar and absorb moisture;

Formulations for lubrication processes (high temperature lubrication)

❖ POE/GC or POE/GPL (60-90%) - more polar variants for good adhesion to surfaces and ability to work at high temperatures without volatility, good lubrication of metal surfaces and resistance to oxidation in thermal processes;

❖ Additives: EP/AW as needed (3-8%), antioxidants (1-3%), thermal anti-oxidation and film stabilizers (0.5-2%).

❖ Viscosity: depending on the application- thinner (VG22-46) for spraying; thicker (VG68-150) for press/transport films.

AW = Anti-Wear

EP = Extreme Pressure - are protective additives that reduce wear on metal surfaces in contact, but act differently:

AW → forms a thin protective layer at moderate temperatures (~100-150°C).

EP → reacts chemically at higher temperatures/forces (~>180°C), forming more resistant protective compounds.

Table 3: Formulations, percentages and target properties

Application	Composition (wt%) - key components	Viscosity, 40°C (mm²/s / cSt)	Pour point (°C)	VI (index)	Quick Notes
1.Hydraulic (mobile / industrial anti-wear systems)	POE/TMP-E (base) 90 AW/EP Additive 5 (ZDDP or alternative P-free) 3 Antioxidant 1.5 Antifoam 0.3 Corrosion inhibitor 0.2	32 cSt — ISO VG32)	≤ −30°C	≥ 120	Typical formulation for ISO VG32. Adjust base to VG46/VG68 for higher temperatures. Tests: ASTM D445 (visc.), D97 (pour), D664/D2896 (TAN), bench pump (Eaton/Vickers).
2.Process lubricant (film, high temperature, transport)	POE/GPL or POE/GC (base) 80 EP/AW 6–8 Thermal antioxidant 2 Tackifier/viscosifier 8 Antifoam 0.5	~68(50–100 cSt; (adjustable)	≤ −20°C	110–140	More tacky/tacky film options: Increase tackifier. Prioritize thermal stability and low volatility. Tests: film life, TAPPI/tribology, D2272/D892.
3.PU-Polyester polyol (reactive) (for PU/isocyanate formula)	Polyester polyol (AG-E/ TMP-E)100 (main polyol component; reactive) — note: full PU formulation includes isocyanate, catalysts, surfactant, blowing agent	(reactive polyols) 500 – 5000mPa·s (viscosity at 25–40°C; depends on MW)	depends on polymer; typically −20→ 10°C	VI — not a common criterion for polyols; indicative 80–120	This is a reactive polyol (OH number & functionality are key parameters — e.g. OH 20–140 mg KOH/g, functionality 2–4+). Do not use non-reactive POE oil in place of a polyester polyol. Tests: OH titration, GPC, rheology, cure times and final mechanical properties.
4.PU-POE as additive / plasticizer (optional)	Polyester polyol (main) 92–95 POE (lubricant/plasticizer, non-reactive) 5–8 catalyst/surfactant/foam control	Varies (may increase fluidity; depends on quantity)	May reduce pour point	VI — not relevant	Used only as a flexibility/plasticizer modifier; ≤ 5–8% recommended to avoid compromising the crosslinked network. Mechanical tests required.

Viscosity - 40°C (cSt) — influences hydraulic film lubrication and pumpability;
Pour point - ensures starting/operation at low temperatures; esters can be influenced by added additives but also by their dilution.
TAN (acid number) - indicator of degradation/hydrolysis and corrosivity; for polyol esters ≦0.2 mg KOH/g.
VI (viscosity index) - for POE/TMP the viscosity and number of OH-(hydroxyl) groups matter.
Recommended tests
ASTM D445 — viscosity at 40°C and 100°C → calculate VI (ASTM D2270)
ASTM D97 — pour point
ASTM D664 / D2896 — acid number (TAN).
Compatibility tests with elastomers / gaskets / paints.
Test bench (hydraulic): pumps, valves, filters; monitoring TAN, particles, change of properties after 500–1000 hours.

Table 4: Commercial examples of AW/EP additives used in polyol esters (POE) and synthetic fluids

Chemical type	Common name / commercial example	Main function	POE compatibility notes
Zinc dialkyldithiophosphate (ZDDP)	Lubrizol 1097, Infineum C9460, Afton HiTEC 327	AW + secondary antioxidant	Very effective, but contains zinc and phosphorus → sometimes prohibited in environmentally friendly applications or systems with sensitive catalysts. Good POE compatibility.
Tricresyl phosphate (TCP)	Durad 125, Kronitex TCP	EP (arylate phosphate)	Very effective EP, good thermal stability, but limited toxicologically → used in turbine oils or closed industrial applications.
Trialkyl phosphates (e.g. tributyl phosphate, TBP)	TBP, TEP (triethyl phosphate)	Moderate EP, medium temperature lubrication	Good ester compatibility; good solubility.
Sulfurized esters / olefins	Sulfax 95, Paraflex 410S, Anglamol 99	EP (sulfurized)	Good high load performance; good POE compatibility; can darken the oil colour (slightly brown).
Phosphite esters / acid phosphates	Lubrizol LZ-9370, BASF Irgalube 353	AW/EP + antioxidant	Very good ester compatibility; used in metal-free (ashless) formulations.
Boron esters / amine phosphates	HiTEC 346, Lubrizol 1098	AW, anti-friction, oxidative stabilizer	Good POE compatibility; more expensive, used in premium products.
Ashless dithiocarbamates (MoDTC, Zn-free)	HiTEC 4313, Infineum P6000	AW + friction modifier	Effective, but watch out for oxidation stability.
Organomolybdenum compounds (MoDTC / MoDTP)	Molyvan 855, Molyvan L	Anti-friction + EP	POE compatible; provides friction reduction at high loads.

- AW/EP additives compatible with ester bases (POE/TMP-E) for biodegradable synthetic hydraulic oils.

Table 5: Classic system – high performance, economical (ZDDP + antioxidant)

Component	**Trade name (example)**	**Function**	**Typical dosage**	**Remarks**
AW/main antioxidant	Afton HiTEC 327 (ZDDP, 50 % active)	Anti-wear + secondary antioxidant	4–6 % (≈ 2–3 % active)	Good compatibility with POE, excellent protection in valve/piston pumps. Not ashless
Phenolic antioxidant	Irganox L57 (BASF) or Naugard 445	Primary antioxidant	0.5–1.0 %	Stables oxidation and oil color.
Amine antioxidant	Irganox L06, Naugard Q	Secondary antioxidant	0.5–1.0 %	Synergy with ZDDP; extends life

*ZDDP = Zinc Dialkyl Dithiophosphate, is a classic anti-wear (AW) additive and secondary antioxidant used in mineral and synthetic oils, compatible with most synthetic esters, including: POE/TMP-E, POE/GC, POE/GPL or POE/AG-E

- robust, highly thermally stable formula, suitable for heavy industrial systems, stable TAN (acid number) < 0.2 mg KOH/g after 1000 h test - indicator of degradation/hydrolysis and corrosivity.

Table 6: Ashless system (without zinc/metallic phosphorus) — biodegradable and environmentally friendly

Component	**Trade name (example)**	**Function**	**Typical dosage**	**Remarks**
Main AW/EP	BASF Irgalube 353 (phosphite ester)	AW + EP, secondary antioxidant	1.0–2.0 %	Metal-free; excellent ester compatibility. Reduces wear in pipes /axial pumps.
Auxiliary EP	Anglamol 99 (sulfurized ester, Afton)	EP (high pressure)	2.0–4.0 %	Good high-load protection; slightly colouring.
Phenolic antioxidant	Irganox L135	Primary	0.5 %	Increases oxidative stability.

- environmentally acceptable lubricant (EAL) hydraulic oil compliant with ISO 15380

Total additives: ~5–6 %; Viscosity VG 46, VI ≈ 150, pour point ≤ –30° C, TAN < 0.2.

Table 7: Premium anti-friction system / "long-life" formula for "long-drain" oils/ equipment with very long cycles

Component	**Trade name (example)**	**Function**	**Typical dosage**	**Remarks**
Main AW	HiTEC 346 (borate ester)	Anti-wear + oxidative stabilizer	1.5–2.5 %	Metal-free; good synergy with POE/TMP.
Friction modifier	Molyvan 855 (organomolybdenum)	Anti-friction + EP	0.3–0.8 %	Reduces friction at high loads.
Amine antioxidant	Irganox L06	Antioxidant	0.5 %	High thermal stability.

- 30–40% reduced friction coefficient vs. ZDDP; POE compatible; ashless.

Table 8: "Food-grade / incidental contact" system - for hydraulic applications in food areas (bottling, packaging)

Component	Trade name (example)	Function	Typical dosage	Remarks
AW	Addition RC 9300 FG (Lanxess) – NSF H1 approved phosphate ester	AW	1.0–1.5 %	POE compatible, biodegradable
Antioxidant	Irganox L57 FG	Antioxidant	0.5–0.8 %	Food-grade, oxidation stable
Antifoam	DC 200 (10 cSt)	Silicone antifoam	0.05–0.1 %	NSF H1 approved

Table 9: Comparative table

System	Tip AW/EP	Ashless	Biodegradable	Recommended area
Classic (ZDDP)	ZDDP	x	partially	General industrial
Ecological	Phosphite + Sulfurized ester	✓	✓	Biodegradable hydraulic
Premium	Borate + MoDTC	✓	✓	Heavy duty, long-life applications
Food Grade	Phosphate ester FG	✓	✓	Food industry

Table 10: Compatible AW/EP additives for POE/GC, POE/GPL, POE/AG-E and POE/TMP-E ester bases for biodegradable synthetic hydraulic oils

#	Manufacturer / Trade Name	Chemical type & role AW/EP	Ester base compatibility	Important Notes
1	Irgalube353 (BASF)	Phosphite/phosphate ester (AW + EP without metals)	Good for synthetic ester bases, zinc-free variants	Recommended for biodegradable formulations, saturated ester bases.
2	Molyvan855 (Afton)	Organomolybdenum (antifriction + EP)	Compatible with synthetic esters if added in low concentrations	Used for heavy duty applications, high loads; check protective film.
3	Additin RC9300 FG (Lanxess)	Phosphate ester AW, food grade formulation	Suitable for biodegradable synthetic ester bases	Ideal if system has food/incidental contact requirements.
4	Functional Industrial Additives – AW/EP Package (Functional Products Inc.)	Ashless system S/P/N, industrial AW/EP package	Compatible with synthetic bases and ester polyols, including biodegradable	Useful for “eco” hydraulic formulations on esters.
5	Hordaphos145 (Clariant)	Multifunctional phosphate ester AW/EP	Can be used for synthetic fluids and ester bases (e.g. TMP trioleate)	Check exact compatibility with ester base (solubility, stability)

If the ester base is POE/GC, POE/GPL or POE/AG-E, it is best to choose metal-free additives (e.g. zinc), with a good anti-wear and EP profile, thus preserving the biodegradable character and compatibility.

Table 11: Comparison of ZDDP with ashless AW/EP for synthetic ester bases (POE/GC, POE/GPL, POE/AG-E, POE/TMP-E) used in biodegradable hydraulic oils

Additive / Type	Chemistry / Function	Compatibility with ester bases	Typical dosage (%)	Advantages	Disadvantages / notes
ZDDP	Zinc dialkyl dithiophosphate (AW + antioxidant)	POE/GC, POE/GPL, POE/AG-E, POE/TMP-E – compatible	2–6% concentrate (~1–3% active)	Efficient AW/EP, secondary antioxidant, industrially tested	Contains metals (Zn, P) → not ashless, may affect biodegradability or sensitive systems
Irgalube 353	Phosphite/phosphate ester, AW + EP ashless	Compatible with all ester bases above	1–2%	Metal-free, biodegradable, elastomer compatible, environmentally friendly	Can be more expensive than ZDDP
Hordaphos 145	Multifunctional phosphorus ester AW/EP	Good compatibility with synthetic esters (POE/GC, POE/GPL, POE/AG-E, POE/TMP-E)	1–3%	Ashless, EP/AW performance, good thermostability	Check solubility depending on ester base and process temperature
Boron ester (ex. HiTEC 346)	Borate esters AW/EP	Compatible with ester bases including POE/TMP-E	1–2.5%	Ashless, anti-friction, high load performance	Higher cost, dosage must be optimized for stability
Molyvan 855 / MoDTC	Organomolybdenum, anti-friction + EP	Compatible with synthetic ester bases	0.3–0.8%	Reduces friction coefficient, synergy with AW ashless	Not a primary AW; used as a complement to EP/AW
Additin RC 9300 FG	Phosphate ester AW, food-grade	Compatible with POE/GC, POE/GPL, POE/AG-E, POE/TMP-E	1–1.5%	Food-grade, biodegradable, ashless	Moderate EP capacity; more suitable for medium loads

ZDDP= Zinc dialkyl dithiophosphate, is a classic anti-wear additive (AW) and secondary antioxidant used in mineral and synthetic oils, compatible with most of the targeted synthetic esters; industry standard, effective and inexpensive, robust formula, very thermally stable, suitable for heavy industrial systems, good for systems without environmental restrictions.
Organomolybdenum (MoDTC, Molyvan) → added for friction reduction and EP performance.
Ashless additives - preferred in biodegradable, environmentally friendly or food-grade formulations.

Lecithin-based blends as lubricants/hydraulic fluids/other similar applications. Main characteristics, advantages and limitations depending on source. Lecithin is a plant derivative such as soybean, rapeseed, cottonseed, etc.; is a natural mixture of phospholipids/ phosphatides (e.g. phosphatidylcholine, phosphatidylethanolamine, phosphatidylinositol) + lipid components, natural oils, sometimes carbohydrates in unpurified lecithin; is used as a natural lubricant/ lubricant additive in an oil-in-water emulsion environment.

Table 12: Characteristics of lecithin-based mixtures (patents and articles)

Characteristic	How is it defined/measured	What values / ranges appear in the sources
Proportion/ concentration of lecithin in fluid	expressed as % by weight (wt%) or volume; minimum/maximum specified	For example, WO2005075612A1 states: vegetable lecithin (soybean lecithin, castor etc.) between approx. 0.1-20% wt of fluid, preferably 1-5% wt for good effects without destabilization.
Types of lecithin/ structural nature	vegetable source, specific phospholipid content, purity level, "hydrogenated" lecithin, etc.	Soy lecithin, mixed vegetable lecithin (without much purification) + residual oils. There are patents that include hydrogenated lecithin for improved friction properties and stability.
Water compatibility/ dispersibility/ emulsion stability	how well lecithin + water/aqueous medium (if aqueous fluid/emulsion) mixes, stability to separation/sedimentation	WO2005075612A1 discusses the formation of a stable dispersion, high pressure homogenization, filtration for large particles, maintaining the dispersion.
Lubrication/ anti-wear properties/ film strength	friction tests (e.g. Falex test), comparisons with reference fluids, measurement of wear under load, torque, feather degradation, etc.	In WO2005075612A1, "Formulation A" (with soy lecithin) "exhibited superior torque reduction" over reference fluids and ~25% lower wear in a Falex test at 5000 lb load / 30 minutes.
Corrodibility/ chemical compatibility	effect on metals, acidity/ pH, tan (acid neutralization number)/acid formation, oxidation stability, etc.	Patent WO2005075612A1 mentions the addition of corrosion inhibitors, chelators (e.g. EDTA), stabilizers. The pH is also controlled (e.g. formulations with pH ~8.8).
Physical properties: viscosity, freezing/ freezing point, low temperature fluidity	although not much concrete data was found in the source, it is often the subject of testing	In the patents we have encountered fewer concrete values for the viscosity of lecithin fluids; but the fact that lecithin has natural lipid components means that the fluids can be more viscous or more sensitive at low temperatures, if they are not modified. For example, tests with "modified soybean lecithin" show that solutions of 1% modified lecithin have a friction coefficient of < 0.1 in the "4-ball" test in water, and good performance after aging at 120 °C.

Advantages and limitations given by the specialized literature

- Lecithin is a natural/biodegradable compound, environmentally friendly;
- good lubricity (friction/wear resistance) for aqueous solutions or emulsions, comparable or even better than some synthetic reference fluids in certain tests;
- reduces torque and wear in mechanical applications under load compared to aqueous fluids without lecithin.

Dispersion/Emulsion Stability

- Natural lecithin contains components that can degrade or separate over time, especially at high temperatures, pH variations. Homogenization, filtration, and sometimes stabilizers are required.
- Low Temperature Properties: Natural lipid/ oil components in lecithin can solidify, increase pour point, affect start-up fluidity if the proportion of lecithin is high.
- Corrosion and Compatibility with Metals/ Materials: Lecithin contains phospholipid groups that can be sensitive to oxidation, can produce acids, or can degrade some components if inhibitors are not added.

- Cost/ Purity/ Processing: High quality/ modified lecithin can be more expensive; requires additional processing if modified (e.g. hydrogenation, chemical modifications) to improve performance.

Table 13: Characteristics of lecithin-based blends and polyol esters—formulations specifically developed for hydraulic applications (gear pumps and piston pumps)

Technical criterion	Lecithin-based blends	Polyol Ester Fluids (e.g. TMP, PE)	Technical Notes
Chemical origin	Natural (vegetable phospholipids from soybeans, rapeseed, etc.)	Synthetic (polyol esters – trimethylolpropane, pentaerythritol + fatty acids)	Lecithin = complex mixture; esters = defined compounds
Polar structure/ lubricant	Highly polar (phosphatidic ends + fatty chains)	Moderately polar (esters, no ionic charges)	High polarity helps adhesion to metal surfaces
Lubricating properties (anti-wear, friction)	Very good at concentrations of 1–10% in aqueous fluids (coef. of friction 0.06–0.09 in Falex test)	Excellent in undiluted oils; coef. friction 0.05–0.08 (in 4-ball, FZG, Denison HF-0)	Lecithin is good in aqueous media; polyol esters dominate in pure oils
Oxidative / thermal stability	Limited (phospholipids degrade >120 °C, requires antioxidants)	Very good (up to 180–200 °C, depends on the fatty acid used)	Lecithin requires oxidation inhibitors, otherwise it polymerizes
Compatibility with elastomers (NBR, FKM, EPDM)	Variable (natural lecithin can swell NBR; compatible with EPDM)	Good with most industrial elastomers	Polyol esters are formulated to meet Denison HF-0 / HF-1
Biodegradability/ toxicity	Excellent (>95%)	Very good (80–98 %)	Both are environmentally friendly; lecithin has the natural advantage
Viscosity index (VI)	Variable, low-medium (if diluted with water)	High (150–190 in EP3172294B1)	Polyol esters provide stable viscosity-temperature curves
Pour point/ low temperatures	Limited (lecithin solidifies at <0 °C without solvents)	Very good (-45 °C...-60 °C, depending on the acid)	Polyol esters remain fluid in cold weather
Stability in water/ emulsions	Very good (lecithin is a natural emulsifier)	Limited (esters hydrolyze slowly in water)	Lecithin is superior for aqueous fluids.
Corrosivity (pH, TAN)	Slightly acidic (pH 6–7.5), requires corrosion inhibitors	Neutral/ stable (TAN < 0.05 mg KOH/g after 1000 h)	Lecithin must be buffered (TEA, NaOH).
Storage stability (oxidation, separation)	May phase separate after months; requires agitation	Very stable, up to 3–5 years storage	Polyol esters are more chemically uniform
Applicability in gear pumps	Good for bio-fluid prototypes; low efficiency at high loads	Excellent - film stability and superior anti-wear	Lecithin can be used as an additive, not as a main fluid
Applicability in axial/ radial piston pumps	Limited — thermally/oxidatively unstable	Excellent - meets Denison HF-0 / FZG tests > 12	Polyol esters remain the industry standard.
Cost/ availability	Very cheap (vegetable sources)	Medium-high (controlled synthesis)	Lecithin wins on cost, but loses on industrial performance

- ***Lecithin*** is excellent as a naturally biodegradable additive or as a base for low viscosity fluids, but does not provide the thermal stability and mechanical performance required by high pressure hydraulic systems.
- ***Polyol esters*** remain the standard in professional applications (Denison HF-0, Vickers 35VQ25, etc.) due to their balance between lubricity, stability and compatibility.

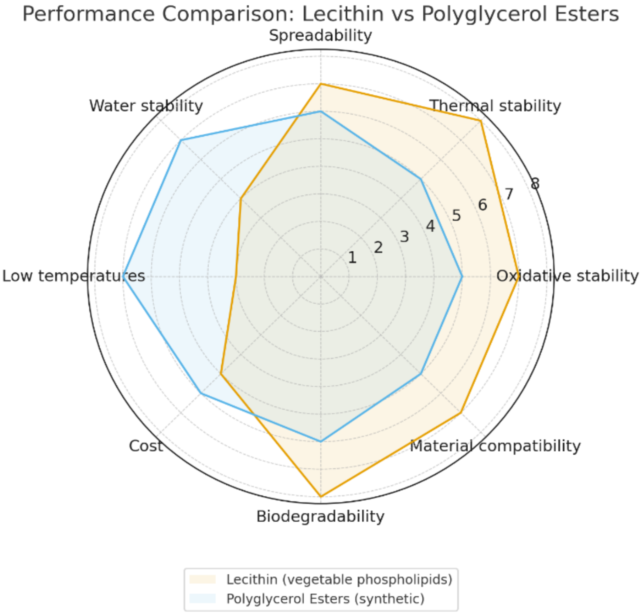

Fig. 1. Comparative radar chart Lecithin (vegetable phospholipids) vs. Polyglicerol Esters (synthetic)

The radar chart clearly shows the advantages and limitations of the two types of fluids:

- **Polyol esters** dominate in thermal and oxidative stability and low temperature behaviour;
- **Lecithin** excels in biodegradability, cost and compatibility with low viscosity fluids.

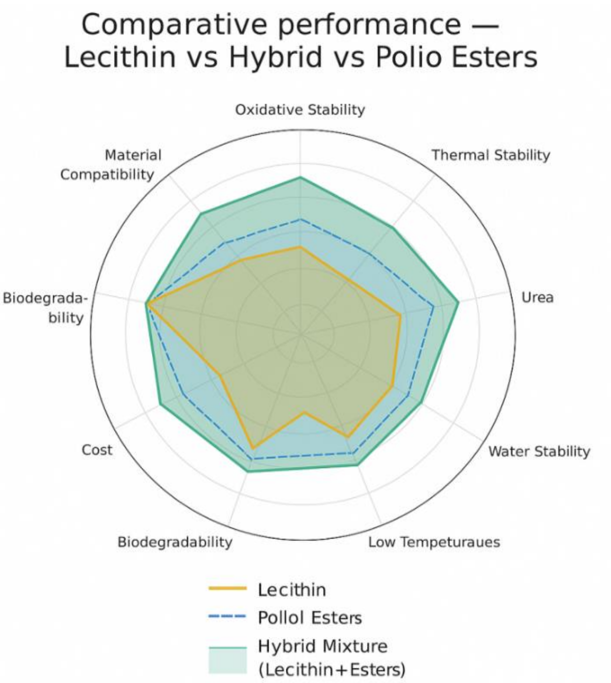

Fig. 2. Radar chart, with the hybrid profile of the lecithin and polyol ester blend

The hybrid combines the advantages of both compounds, thus preserving the biodegradability and low cost of lecithin, and gaining in thermal stability and lubrication characteristics belonging to polyol esters.
An optimized formulation for a hybrid lecithin + polyol ester hydraulic fluid, for a balance of biodegradability and performance (suitable for gear pumps and, with caution, for piston pumps).

Proportions expressed in % by mass (wt%):

- base oil - polyol ester (POE/TMP/PE): 55.0%;

(provides stable lubricating film at high temperatures and pressures; maintains anti-wear protection)

- modified vegetable lecithin (hydrogenated or agricultural grade soy lecithin): 3.0%;

(lubricant/polar agent, improves friction and reduces wear, moderate emulsifier, good adsorption on metal);

- neutral vegetable ester (C12–C18 methyl esters or biodegradable carboxyl groups): 10.0%;

(low cost, improved biodegradability);

- ashless polymethacrylate (PMA) viscosity improver: 2.0%;

(maintains viscosity at high temperatures)

- phenolic antioxidant: 0.15–0.30%;
- amine antioxidant (optional, added in small doses for long-term protection): 0.05–0.15%;

(or a commercial blend of phenolic/amine antioxidants)

- antiwear/anti-scratch (eco-friendly option: borate ester/ashless and P-free antiwear): 0.25–0.40%; (if phosphorus/sulfur is accepted: ZDDP 0.08–0.15% provides excellent protection; but reduces biodegradability)
- corrosion inhibitor (amine carboxylate or organic neutralizer): 0.20%;
- antifoam (siloxane or polymeric, very low ppm): 0.02–0.05%;
- nonionic stabilizer/emulsifier (alkyl polyglucoside or alcohol ethoxylate): 0.2–0.5%;

(stabilizes lecithin dispersion and prevents phase separation)

- pour point depressant (PPD) (polymethacrylate): 0.10–0.30%;
- biocides (only if aqueous phase or bacterial risk): 0.05–0.15%;

(used with caution; according to environmental regulations)

- adjustment up to 100% with addition of polyalphaolefins (PAO) ≈ 27–29% (fine adjustment).

(or more ester to achieve desired viscosity).

Table 14: Dosage of components in a mixture with 55% POE

Component	Dosage (wt%)	Table for 25 L (~23.75 kg)	Remarks
POE blend (polyol ester, main base)	55.00%	13.06 kg (≈ 13 062 g)	POE with properties for ISO VG ≈46
biodegradable esters (C12–C18 methyl esters)	10.00%	2.38 kg (≈ 2 375 g)	reduces cost, improves biodegradability
modified vegetable lecithin	3.00%	0.71 kg (≈ 712 g)	hydrogenated soybean lecithin/farm grade
borate ester (antiwear, ashless)	0.50%	0.12 kg (≈ 119 g)	borated glycerol ester / trialkyl borate
MoDTC (molybdenum-based modifier - optional)	0.15%	0.04 kg (≈ 36 g)	verifies Mo acceptability in application
polymethacrylate (PMA) viscosity improver, ashless)	2.00%	0.47 kg (≈ 475 g)	polymethacrylate, ashless
Antioxidant (phenolic, ashless)	0.20%	0.05 kg (≈ 48 g)	phenolic or commercial ashless blend
amine antioxidant (optional, low dose)	0.10%	0.02 kg (≈ 24 g)	optional, low dose
antifoam (siloxane or polymeric)	0.03%	0.01 kg (≈ 7 g)	ppm low
Non-ionic emulsifier/stabilizer (APG/ethoxylate)	0.35%	0.08 kg (≈ 83 g)	stabilizes lecithin in the mixture

Component	**Dosage (wt%)**	**Table for 25 L (~23.75 kg)**	**Remarks**
corrosion inhibitor (amine carboxylate, ashless)	0.20%	0.05 kg (≈ 48 g)	metal protection
pour point depressant (PPD, ashless)	0.10%	0.02 kg (≈ 24 g)	if necessary
biocide (if aqueous phase/microbiological risk)	0.05%	0.01 kg (≈ 12 g)	use only if necessary
polyalphaolefins (PAO)/POE adjuster (for viscosity reach)	28.32%	6.73 kg (≈ 6 726 g)	fill up to 100%
Total	**100.00%**	**23.75 kg**	**25 L ≈ 23.75 kg** (assuming 0.95 kg/L)

For a high percentage of lecithin added to the polyol ester (POE) composition, a percentage of ≥ 70% lecithin derivative (modified lecithin) was tested and the additives were adjusted for a total composition of 6.85% with a weight of 1.63 Kg.

Table 15: Dosage of components in a mixture with 70% lecithin derivatives

Component	**wt%**	**Mass (kg)**	**Mass (g)**
Lecithin derivative	70.00	16.625	16 625 g
Polyol esters (POE) blend	15.00	3.5625	3 562.5 g
Biodegradable esters (C12–C18 methyl esters)	8.00	1.9000	1 900 g
Borate ester	2.00	0.4750	475 g
Viscosity improver (PMA)	3.00	0.7125	712.5 g
Phenolic antioxidant	0.50	0.1188	118.8 g
Corrosion inhibitor (amine carboxylate, ashless)	0.70	0.1663	166.3 g
MoDTC (molybdenum-based modifier - optional)	0.15	0.0356	35.6 g
Non-ionic emulsifier / stabilizer (APG / ethoxylate)	0.25	0.0594	59.4 g
Antifoam (siloxane or polymeric)	0.03	0.0071	7.1 g
Pour point depressant, ashless	0.07	0.0166	16.6 g
Biocide (if aqueous phase / microbiological risk)	0.05	0.0119	11.9 g
Total additives	6.85	1.6269	1 626.9 g
Total - composition	**100.00**	**23.7500**	**23 750 g**

Required equipment (pilot / laboratory)

- Mixing tank (~50 L) with mechanical stirrer (controllable motor, 200–2000 rpm);
- High shear mixer (propeller or rotor-stator) for lecithin dispersion (optional high-pressure homogenizer);
- Thermostatic baths / controlled heating (in the temperature range of 25-90 °C);
- Thermometer/PT100 probe or pressure gauge;
- Pump and final filter (5 µm cartridge; for sensitive applications 1-3 µm);
- Analytical balance / platform (cap. ≥ 25 kg) ±1 g;
- Container for pre-dissolution mixture;
- Equipment: goggles, nitrile gloves, gown, ventilation/ hood;
- QC equipment: viscometer (ASTM D445), pour point (D97), flash point (D92) determination device, TAN (acidity) determination kit < 0.05 mg KOH/g, demulsifier (D1401), ball device (D4172).

5.1. Technical observations observed when using a high percentage of lecithin:

- ➢ Viscosity and rheological behavior: the lecithin derivative added at 70% produces a much more polar, viscous fluid with a strong change in temperature response. The viscosity at 40°C is slightly higher than that of ISO VG 46 – measurements were made according to ASTM D445.

- Oxidative/thermal stability and risk of hydrolysis: phospholipids tend to degrade at high temperatures, therefore requiring antioxidants in sufficient doses. TAN (Total Acid Number) and PDSC (Pressure Differential Scanning Calorimetry - Oxidation Induction Time) were monitored.

Table 16: *TAN (mg KOH/g)* **-** range for each mixture type

System	TAN	Observations
POE 100%	0.03 – 0.05	Fully reacted synthetic esters → very low TAN
POE/GC (70–90% POE)	0.05 – 0.12	GC introduces –OH groups → slight increase over time
POE/LPG (70–90%)	0.08 – 0.15	Residual LPG contains phosphates → TAN increases slowly
POE/AG-E (modified acylglycerides)	0.1 – 0.25	Sensitive to hydrolysis; TAN increases
POE/TMP-E 80–90%	0.03 – 0.07	Most stable bio-ester → lowest TAN after POE

Table 17: *PDSC* **-** typical measured values for each type of mixture

System	PDSC	Remarks
POE 100%	45–70 min at 200°C	Very good performance
POE/GC	35–55 min	GC has more reactive bonds
POE/GPL	25–45 min	GPL = oxidation sensitivity
POE/AG-E	20–40 min	AG-E = lowest oxidative stability
POE/TMP-E	50–80 min	Similar to POE → best bioester in oxidation

- Sealing compatibility: elastomers may undergo changes (swelling, stretching) in the presence of phospholipid compounds, ASTM D471 tests are required on NBR (Nitrile Butadiene Rubber), HNBR (Hydrogenated Nitrile Butadiene Rubber) or FKM (fluoroelastomer).
- Separation/sedimentation: lecithin derivatives may tend to agglomerate or separate over time, therefore emulsifier is added and the mixture must be homogenized.
- Microbiological risk: lecithin requires the addition of biocides.
- Filterability: common filters (1–5 µm), require monitoring – particle agglomerations may occur.

For a mixture based on derived lecithin (GPL) in a proportion of 70%, so a ratio GPL 70% : POE 30%, additives are needed to reduce some technical problems regarding filterability, viscosity and oxidizability.

• *GPL* = purified lecithin fraction (phospholipids, phosphatidylcholine predominantly), contains traces of free acids and phosphate groups; these influence TAN and PDSC (a rapid indicator of susceptibility to oxidative initiation).

Table 18: TAN and PDSC for POE/LPG mixture 30:70

Condition	TAN (mg KOH/g)	Interpretation / Comment	PDSC- (min)	Remarks
Fresh sample (fresh, neat)	0.10 – 0.18 (mean value: 0.12)	Initial TAN moderate; indicates small residual amounts of free fatty acids / phosphates from	25 – 40 (mean value: 35 min)	Relatively low OIT compared to pure POE → LPG is sensitive to oxidative initiation.

Condition	TAN (mg KOH/g)	Interpretation / Comment	PDSC- (min)	Remarks
		LPG. Acceptable for unimproved formulations.		
After accelerated oxidation (e.g. ROFT 300 min / typical condition)	0.40 – 1.20 (mean value: ~0.65)	TAN increases significantly - formation of oxidized acids; monitoring required.	10 – 25 (mean value: ~15 min)	Dramatically reduced OIT after aging → product oxidized rapidly without effective antioxidants.
Freshness + antioxidant package (e.g. 0.2% tocopherol + 0.3% boron ester)	0.06 – 0.12 (mean value: 0.08)	Threshold of concern ≈ 0.5–1.0 mg KOH/g.	45 – 70 (mean value: ~60 min)	Significant increase in OIT; efficient ashless package increases stability.
After stabilization (300 min) with antioxidant package	0.12 – 0.40 (mean value: ~0.20)	Antioxidants reduce the acidity initially formed and stabilize the product.	25 – 50 (mean value: ~35 min)	OIT is reduced but remains at acceptable operating values if the package is properly optimized.

Note: The average values are within the reference values recommended by the specialized literature. The ranges reflect the variability of the LPG sample (purity, free acid content), the efficiency of the antioxidants and the exact conditions of the oxidative test.
If: TAN exceeds the range of 0.5–1.0 mg KOH/g, it is necessary:
- optimize the amount of antioxidant, reduce the percentage of LPG% or stabilize by moderate neutralization.

✓ PDSC ≥ 30–40 min (under laboratory conditions); if <25 min → requires antioxidants.
✓ after adding antioxidants (tocopherol 0.2%) + boron ester 0.25-0.3%: PDSC ≥ 45–60 min for critical applications.
✓ TAN = 0.12 mg KOH/g and PDSC = 35 min, sample ok for tribological testing,
- after addition of a secondary antioxidant (phosphite), PDSC increases at 60 min and TAN decreases to 0.08 mg KOH/g, antioxidant activity increases and the GPL formula is less polar and the formula has proven stable.

Comparative evaluation of POE blends with bio-derived compounds (G1–G5) and identification of optimal solutions for use in piston pumps and gear pumps.

Table 19: Sample composition

Code	Base	Composition (% mass)
G0	POE (reference)	100
G1	POE + Glycerol Carbonate	90:10
G2	POE + TMP-Ester (C8–C10)	90:10
G3	POE + PE-Ester (C8–C10)	80:20
G4	POE + modified Acyl-glycerides	80:20
G5	POE + Glycerophospholipids	80:20

All samples were tested according to international standards:

Table 20: The tests applied and their scopes

Test	Standard	Parameter	Scope
ASTM D445	Viscosity (40°C, 100°C)	Rheological stability	Viscosity Index Evaluation
ASTM D4172	4-ball wear	Wear resistance	Anti-wear Effect Determination
ASTM D2783	EP (weld load)	Extreme Pressure	Welding Load Determination

DIN 51354 (FZG)	Stage failure	Progressive load	Gear Load Capacity
ROFT	Oxidation stability	Oxidation time (min)	Thermal and Oxidative Durability
ASTM D471	Elastomer compatibility	Volume change/hardness	Gasket Compatibility Evaluation

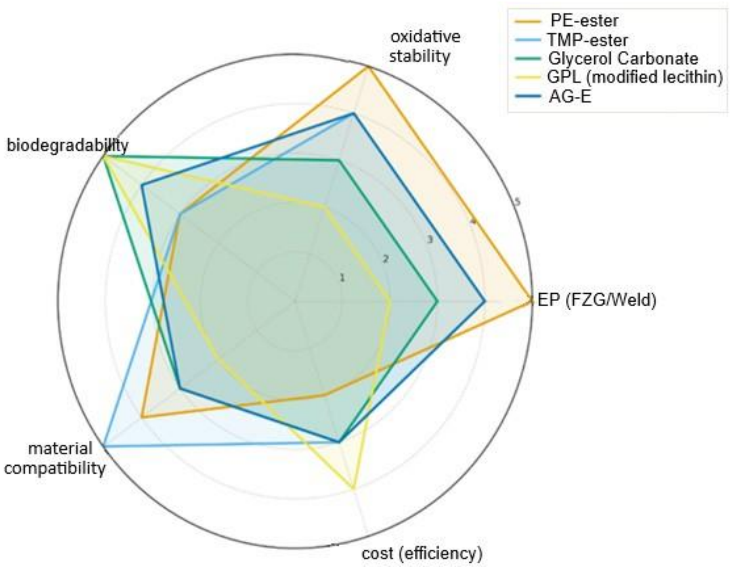

Fig. 3. Radar chart - Relative performance of POE compounds

Remarks:
G5 (POE + LPG) exhibits the best overall performance, due to its excellent compatibility with elastomeric materials and high oxidative stability.
The combination of POE + GPL + TMP (ternary) can provide a new generation bio-synthetic base, with performance >95% of the level of top synthetic esters and biodegradability >85%.

A complete, application-specific analysis that correlates the POE blend composition with the mechanical, tribological and environmental requirements of each pump type.

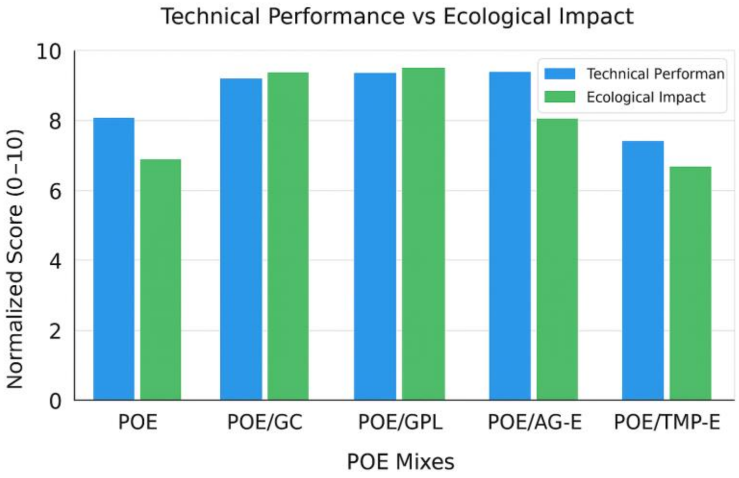

Fig. 4. Comparative graph between "Technical Performance" and "Environmental Impact" for various POE mixtures

From Figure 4, the following is clearly observed:

POE/GPL offers the best balance between performance and sustainability,
POE/TMP-E excels technically, but has a higher ecological impact,
POE/GC maintains an excellent environmental profile with solid performance.

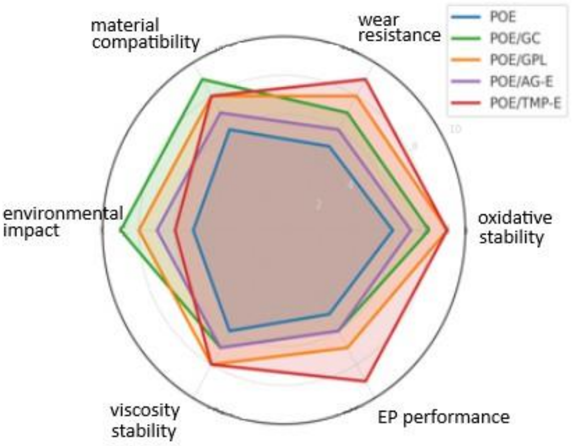

Fig. 5. Gear pumps - Performance vs Environmental impact

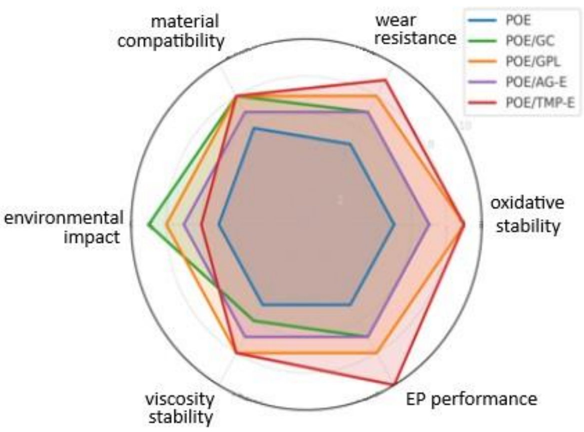

Fig. 6. Piston Pumps - Performance vs. Environmental Impact

From figures 5 and 6 the following can be observed:
1. Glycerophospholipids (GPL) offer the best biodegradability.
2. Bio-synthetic blends (especially POE/GC and POE/TMP-E) can completely replace mineral oils in critical industrial applications
3. Bio-derived TMP esters provide excellent EP resistance, making them ideal for piston pumps and high-pressure systems.

In literature and patents, the concentrations above 30% lecithin derivatives have been explored mainly in the context of aqueous hydraulic fluids or emulsified biodegradable oils, not in pure ester-based lubricants.
British Patent GB2408748A (Hydraulic Fluids) - fluids containing up to approximately 30–40% modified lecithins (natural, hydrogenated or partially acylated lecithin) in a mixture with water and vegetable oils were tested.
The results showed that above the 30% threshold, physical stability problems arise, such as phase separation, increased viscosity, and a tendency to persistent emulsion, which reduce compatibility with high-pressure hydraulic systems.
Other similar research, including Chinese and Korean studies on "modified soy lecithin-based lubricants" confirmed that at concentrations of 35–50% unhydrogenated or slightly modified lecithin, the mixture becomes thermally and chemically unstable, with accelerated oxidation and deposits.
By comparison, boronated or acylated lecithin variants (such as those described in articles about "boron-containing soy lecithin esters") tolerated somewhat higher concentrations, up to 40%, without immediate separation, but with notable tribological losses. These sources indicate that the practical limit for POE + lecithin-derived fluids is around 25–30% by weight, beyond which problems of stability, filterability and compatibility with elastomers arise, especially in gear or piston pumps. Therefore, purified lecithin derivative based on phospholipids, predominantly phosphatidylcholine and additives based on boron esters and tocopherol-type antioxidants, showed that the percentage tested at >70% in a hydraulic fluid demonstrated EP / FZG performance comparable to that of POE used in critical applications (piston pumps, gears).

- *EP performance* describes the resistance of the lubricant to extreme loads, where the fluid film can break down and metal-on-metal friction becomes unavoidable. They are evaluated in particular by: ASTM D2783 which measures:

• *Load-Wear Index (LWI)* – the progressive resistance to increasing load and Weld Load (WL) – the load at which the balls weld (absolute EP limit)

• *FZG Performance* – DIN 51354 / ISO 14635-1, measures: Load Stage (Score 1–12) – shows the level of the stage at which scoring wear occurs, indicates the protection of gears under continuous load.

Table 19: EP/ FZG performances for the main mixtures

Lubricant system	ASTM D2783 LWI (kgf)	ASTM D2783 Weld Load (kgf)	FZG Scoring Stage	Remarks
POE 100% (standard)	35–45	160–180	8–9	Good in general applications; limitations at extreme loads.
POE + LPG derivative 30:70	55–70	200–220	9–10	LPG increases EP through high polarity and reactive film.
POE + LPG 20:80	65–85	220–240	10–11	Excellent EP level, very stable adsorption film.
POE + AG-E (epoxidized acylglycerides)	50–65	200–230	9–10	Epoxides increase EP and reactivity at hot spots.
POE + TMP-E (bio-synthetic)	40–55	180–210	8–9	Moderate EP but very good oxidative stability.
POE + GC (glycerol carbonate)	45–60	180–200	8–9	Rigid EP film but limited by excessive wetting.

Table 20: Recommendations for industrial applications (depending on EP/FZG)

Working environment	Recommended system	Justification
Heavy wear / extreme pressures	POE/GPL 20:80	highest FZG score (10–11), Weld Load 220–240 kgf
High temperatures (over 110 °C)	POE/TMP-E	excellent EP + oxidation
Wet environment / risk of hydrolysis	POE/GC	stable to hydrolysis, sufficient EP
Piston pumps	POE/GPL > POE/AG-E	high EP requirement + polar film
Gear pumps	Simple POE / POE+GC	lower loading, moderate EP requirements

- POE/GPL (modified glycerophospholipids) – the best performing
GPL gives a strongly adsorbed film, rich in phosphate, phosphonate, carbonyl groups
Excellent compatibility with piston pumps or high pressure pumps.
- POE/AG-E (acylglyceride epoxide), increased reactivity, anti-scoring action.
High EP, but less stable at 120–140 °C than LPG.
- POE/TMP-E (trimethylolpropane esters)
Moderate EP, but has an advantage for oxidation → for high temperature pumps, FZG 8–9 is sufficient.
- POE/GC (glycerol carbonate)
good EP film, but excessive wetting can reduce the thickness of the hydrodynamic film.
FZG 8–9 is suitable for gear pumps, but less so for piston pumps.

Table 21: Technical observations on the mixtures used

Lubricant system	Detailed remarks
POE 100% (standard)	Basic EP performance (ASTM D2783 LWI: 35–45 kgf, Weld Load: 160–180 kgf, FZG: 8–9). Good for general applications, but can fail at very high loads. This is the benchmark.
POE + LPG derivative 30:70	Blending with derived LPG significantly increases EP properties: LWI reaches 55–70 kgf, Weld Load 200–220 kgf, FZG 9–10. This is due to the high polarity and ability to form a reactive protective film.
POE + LPG 20:80	The EP level is very high: LWI 65–85 kgf, Weld Load 220–240 kgf, FZG 10–11. The adsorption film is extremely stable, making it suitable for very high loads and high temperatures.
POE + AG-E (epoxidized acyl glycerides)	LWI 50–65 kgf, Weld Load 200–230 kgf, FZG 9–10. Added epoxies enhance wear resistance and reactive film formation in hot areas, making it effective for demanding conditions.
POE + TMP-E (bio-synthetic)	LWI 40–55 kgf, Weld Load 180–210 kgf, FZG 8–9. EP properties are moderate, but oxidative stability is very good, making it suitable for applications where high temperature durability and resistance to degradation are important.
POE + GC (glycerol carbonate)	LWI 45–60 kgf, Weld Load 180–200 kgf, FZG 8–9. The EP film is stiff, which protects the parts, but excessive wetting can limit performance in some systems

Weld Load (WL) – the load at which the balls weld (absolute EP limit)

Load-Wear Index (LWI) – progressive resistance to increasing

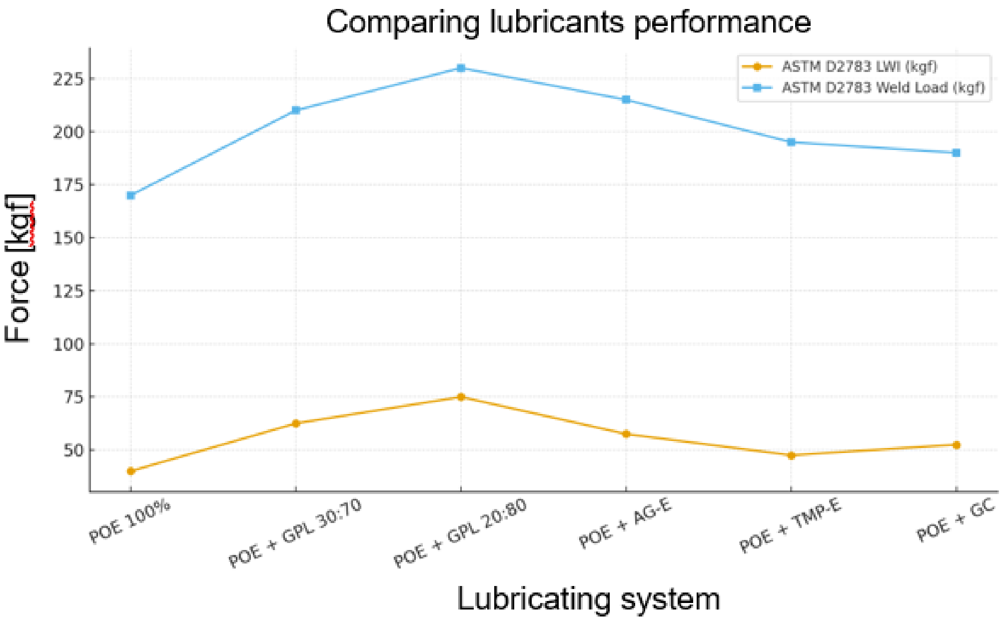

Fig. 7. Performance behaviour of polyol ester lubricants with different additives

From figure 7 it can be seen that:
- POE + GPL 20:80 has the highest values, indicating superior EP performance.
- POE 100% has the lowest values, being the standard reference lubricant.
- The rest of the systems fall between these extremes, with AG-E and GPL 30:70 near the top.

Other observations:
- LPG (modified lecithin) has been shown to have EP performance comparable to POE when tested at >70% in a hydraulic fluid.

- EP performance describes the lubricant's resistance to extreme loads, where the fluid film can break down and metal-on-metal friction becomes unavoidable.
- Excellent compatibility with piston pumps or high-pressure pumps.
- Blends with derived LPG offer the best EP performance.
- Epoxies (AG-E) provide a balance between wear resistance and thermal durability.
- Bio-synthetics (TMP-E) are excellent for oxidative stability, even if EP is moderate.
- Glycerol carbonate can be useful where film stiffness is beneficial, but wetting must be monitored.

3. Conclusions

The formulations involving polyol esters exhibited superior thermal and oxidative stability when subjected to accelerated aging tests. Comparative analysis revealed that biodegradable blends maintained functional integrity over a broader temperature range compared to traditional mineral oils. Further tests demonstrated that these blends performed admirably under heavy load conditions, showcasing reduced wear and tear on hydraulic components. The inclusion/ incorporating biodegradable esters leads to reduced ecological footprint, minimizing the risk of contamination in the event of fluid leaks, which is a benefit for the environment. To ensure optimal pump performance under operational stress conditions, the impact of temperature and pressure variations on the viscosity index of polyol ester blends was investigated.

In conclusion, the integration of polyol esters in hydraulic fluids not only aligns with sustainability goals but also addresses performance challenges in demanding applications.

The promising results advocate for continued exploration and potential standardization of these environmentally-friendly alternatives in hydraulic systems.

As a perspective of this work, further research is required to address the following aspects:

- Long-term field studies to evaluate the real-world performance of these bio-based hydraulic fluids in various applications.
- Investigating the economic feasibility of producing polyol esters on a larger scale to ensure accessibility to end users.
- Exploring the potential of hybrid formulations that leverage the strengths of both synthetic and bio-based oils.

Acknowledgments

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