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Resilient and Renewable: TOFA Supply Chain Outlook and Bio-Oil Innovation for Oilfield Fluids

Allison Proctor, Megan Wilt, Kraton Corporation

Abstract

Tall oil fatty acids (TOFA), derived from the Kraft pulping of softwood, are critical components in oilfield drilling fluid formulations. Known for emulsification and lubricating properties, TOFA is used in OBM and WBM systems. Its molecular structure containing carboxylic acid groups and C_{18} carbon chains enables a range of chemical reactions including esterification, amidation, and saponification thereby, making TOFA highly adaptable to demanding downhole conditions.

Recent market dynamics, i.e., the closure of paper mills and fluctuations in crude tall oil (CTO) pricing, have raised concerns about the long-term availability of pine-derived products. However, CTO production capacity remains stable and well-supported. The continued growth of softwood pulp—driven by demand for packaging products—is projected to reach a compound annual growth rate (CAGR) of 4.5 % by 2033, reinforcing the viability of CTO as a sustainable feedstock. The technical attributes that make TOFA a versatile molecule in drilling mud formulations are highlighted. Additionally, the upstream supply chain of CTO is examined to 4address misconceptions about its availability and showcase the resilience of the tall oil industry.

A CTO derived product is also introduced—engineered to function as an additive in lubricant systems. The bio-oil delivers performance comparable to isomerized olefins, offering a renewable alternative for demanding drilling environments. By connecting supply chain fundamentals, product functionality, and downstream innovations, the continued and future strength of CTO and its derivatives are affirmed.

Introduction

The pine chemical industry plays a central role in converting forest-derived coproducts into high-value, performance-driven materials used within the energy sector. At the core of pine chemistry is CTO, a renewable byproduct of the Kraft pulping process that serves as the primary feedstock for a wide range of specialty chemicals. Through refinement, CTO is separated into key derivative streams—TOFA, tall oil rosin (TOR), distilled tall oil (DTO) and pitch fractions—each offering unique functional properties valued in upstream oil and gas operations.

Recent market dynamics, i.e., the closure of paper mills and fluctuations in CTO pricing, have raised concerns about the long-term availability of pine-derived products. As a leading global refiner of crude tall oil in the world, Kraton has a thorough understanding of the market ins and outs and a perspective of its long-term viability.

This discussion addresses common misconceptions about the pulp and paper market, its connection to CTO, and the key factors driving continued industrial growth. The chemical versatility of TOFA and the pine based bio-oil are also reviewed

CTO Supply Chain and Logistics

Understanding the industrial dynamics is essential for evaluating current and future trends in CTO supply, TOFA market behavior, and downstream application growth—particularly in sectors like oilfield chemistry where security of supply, product consistency, and sustainability are strategic considerations.

The pine chemical industry is inherently tied to forest management and the long-term stability of global pulp production. Therefore, its supply chain operates differently from other chemical value chains. Pine-derived chemicals (e.g., TOFA, TOR, DTO and pitch) enter the supply chain via the Kraft pulping process.

Softwood chips are cooked in a basic solution to separate cellulose fibers for paper. During the process, natural pine extractives are digested into the process liquor. The soapy layer is skimmed from the solution and later acidulated to be converted into CTO.

Although mill closures are often attributed solely to declining paper consumption, the reality is far more nuanced—and only loosely connected to CTO availability. Market shifts between softwood and hardwood pulp, along with persistent industry challenges such as overcapacity and cost competitiveness, play a significant role in determining which mills remain viable. At the same time, growing demand for packaging continues to reshape the landscape, driving new investment and altering long-term expectations for pulp and paper production.

A clearer understanding of market dynamics requires examining the distinct roles that hardwood and softwood pulps play within the global pulp supply chain.

Hardwood pulp is used in the production of printer paper, writing paper, tissues and tissue paper. The short fibers of hardwood give the preferred level of softness for these products (Paper Pulp Mill, 2018). Conversely, softwood pulp is critical for packaging due to its long fibers which provide the strength needed for boxes. Softwood pulp is used in tandem with hardwood pulp in hygiene products to add strength to tissues and towel products (Sharma, 2025). Given the ever increasing demand of e-commerce sites, corrugated boxes and packaging trends are major contributing factors to what reports say is a 4.5 % CAGR of softwood pulp over the next five to seven years (Sharma, 2025).

Korpack, a top manufacturer of packaging in the US, reported that the global corrugated box and container manufacturing market was valued at $429 billion in 2024 and is projected to grow to $807 billion by 2034. The same report claimed that e-commerce growth is supported by sustainability initiatives and versatility in growing markets like pharmaceuticals (Korpack, 2025). The upward trend in packaging along with an increased demand for hygiene products contribute to increased demand in both softwood and hardwood pulps. The demand is outpacing the decline in printer paper and newsprint.

While fiber mix plays a central role in mill strategy, the broader economic context—particularly industry overcapacity and cost competitiveness constraints—further shapes long-term mill viability. During the COVID-19 pandemic, e-commerce surged. The global containerboard capacity jumped approximately 10 % (roughly 20 million tons) from 2019 to 2021 (Franklin, 2023). This surge saw producers add capacity faster than long-term demand warranted. Once retail normalized and exports softened, the system was left long on supply thereby, causing North American producers to remove around 9.5 % of containerboard capacity by 2025 (Franklin, 2023).

Cost competitiveness has affected paper mills as well. PCA's Wallula facility closed due to high power costs which rendered them uncompetitive (Beaver, 2025). Likewise, Domtar's Espanola mill shut down due to its age, cost of maintenance needs, and operational complexity that made continued operation unviable (White, 2023). However, with mill consolidation comes re-investment.

While pulp and paper companies are closing older more expensive mills, there is investment in newer, cost-competitive mills to keep up with ongoing packaging demand. For example, International Paper (IP) is adopting a new 80/20 operating philosophy which focuses resources on the highest value customer segments and simplifies operations. As part of this shift, IP is closing high cost or low value assets while building new, strategically positioned capacity. IP is investing $250 million in its Riverdale mill in Selma, Alabama to convert an uncoated freesheet line to a containerboard line (Pyzyk, 2025). IP is also opening a new containerboard facility in Waterloo, Ohio in late 2026. The site is set to be the biggest corrugated box plant in the country (Phillips, 2025).

Green Bay Packaging has planned a $1 billion expansion of the mill in Morrilton, AR. The expansion would more than double the current pulping capacity (Forisk, 2025). Additionally, Surfit Westrock sought to support its growth in the packaging markets by investing $65 million for the installation of a corrugated box line (Paper Advance, 2025). So, while closures dominate headlines, the reinvestment following the closures is building a healthier, more competitive mill base that supports continued stability in CTO supply over the long term.

CTO refiners have also invested in site assets. Kraton recently invested $35 million to upgrade CTO distillation towers at Panama City, Florida. The work was completed in November 2023 to improve efficiency, product consistency, and long-term supply reliability for CTO derived streams. The upgrade was the site's largest capital investment in 50 years.

CTO/TOFA – Sustainability and Consistency

Not only is TOFA a preferred emulsifier in the oil and gas segment for its performance, but it also carries an exceptional sustainability profile. TOFA is 100 % biobased, is of non-animal origin, and does not compete with food crops for land.

CTO production does not contribute to deforestation. Pulp mills based in Europe and North America have well defined, stringent regulations on managing forests responsibly. This includes practices that help maintain the health, biodiversity, productivity, and longevity of a forest (AF&PA, 2024). In most cases, CTO suppliers are required to hold a valid chain of custody certification to ensure traceable, sustainable, and responsible sourcing of the fibers used as feedstocks.

Weather and climate impact a tree's composition. By harvesting trees aged 10 to 40 years, the perennial variation is mitigated and a consistent product is obtained (Table 1).

Table 1: Iodine values of neat TOFA grades

	Iodine Value (mg of I_2/g sample)
Grade 1	125
Grade 2	125

TOFA is industry leading in product predictability. The consistency of TOFA's feedstock can be contrasted with those of soybean and palm oils and tallow. The compositions of soy and palm oils can vary with genotype, growing region, maturity group, and temperature. Similarly, tallow's profile shifts based on animal genetics, diet, and specific fat source. As CTO, the less refined precursor to TOFA, is not predicated by agricultural cycles like seed oils, both CTO and TOFA provide product consistency.

TOFA Versatility – Structure Fundamentals

The three main fatty acids (FA) of TOFA are oleic acid ($C_{18:1}$), linoleic acid ($C_{18:2}$), and linolenic acid ($C_{18:3}$). The FAs are shown in Figure 1. The polar characteristics, arising from the carboxylic acid group and the fatty chain, have made fatty acids versatile molecules in applications from industrial soaps and coatings to emulsifiers and thickeners. Oleic acid is a key fatty acid for lubrication characteristics due to the *cis* double bond configuration at the C_9 position.

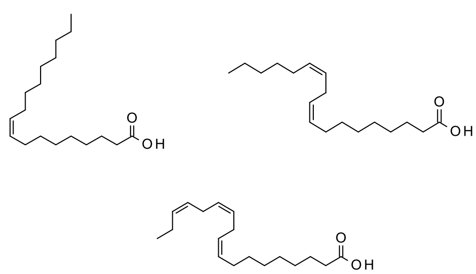

Figure 1: Structures of oleic acid (top left), linoleic acid (top right), and linolenic acid (bottom)

TOFA is used in inverted emulsions. When reacted with a calcium salt, the molecules orient themselves opposite to that which is found in traditional emulsions. The lipophilic carbon chains interact with nonpolar, organic constituents while the hydrophilic carboxylic acid groups interact with polar substances such as metal surfaces and water intrusions.

The dipole moment of the carboxylic acid group (-COOH) lends low volatility, higher flash points and higher thermal stability to the system. This is partly due to the stability of the chemical bonds between the carbonyl carbon and adjacent oxygens (Wade, 2013). Those bonds are more stable than a carbon-carbon bond.

Table 2 shows the thermal stability of two TOFA grades. When analyzed via thermal gravimetric analysis (TGA), the FAs were stable at temperatures greater than 180℃.

Table 2: Decomposition temperatures of TOFA grades via TGA

	Decomposition Temp. (℃)
Grade 1	193 (379℉)
Grade 2	183 (361℉)

TOFA Versatility – Functionalization

The -COOH group can undergo the following reactions: esterification, saponification, epoxidation, amination, reduction to an alcohol or ketone and decarboxylation to a hydrocarbon (Wade, 2013). Alkene oligomers can be synthesized via a Lewis acidic pathway (Otter, 1968; Parfenova, 2024; Yi, 2021). The oligomeric derivatives of TOFA are depicted in Figure 2.

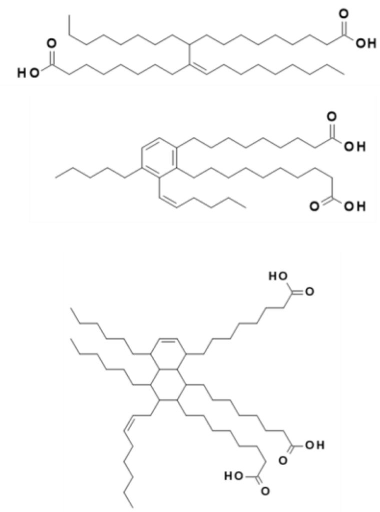

Figure 2: Example structures of dimer and trimer molecules of TOFA

The main constituent of dimerized TOFA is a C_{36} dibasic acid. Two functionalities are gained for every one molecule upon dimerization. The ratio is higher for trimer acids. Oligomerization increases the molecular weight and viscosity of the system while retaining the -COOH groups for additional chemistry. Viscosity ranges of 3,500 – 40,000 cSt and acid values of 189 – 194 have been observed, making dimerization a versatile TOFA upgrade.

Amides of TOFA have also been used to increase the viscosity of the drilling fluid. Aminic analogues of TOFA are multifunctional and have found use as emulsifiers, viscosity modifiers and corrosion inhibitors. Nitrogen compounds have an affinity for steel, hence why molecules like imidazolines, are efficient corrosion inhibitors for ferrous materials.

The performance of a TOFA system can be further customized to the needs of the application. When esterified with glycerol, the pour point of TOFA decreases. Table 3 lists the pour points of TOFA and its ester derivative.

Table 3: Pour points of neat TOFA and esterified TOFA. ASTM D5950 followed.

Substrate	Pour Point (℃)	
	neat	glycerol ester
Grade 1 TOFA	5.6	-16.0
Grade 2 TOFA	1.0	-18

Both dibasic and polyol esters have exhibited high film strength (low CoF), shear stability and good thermal/oxidative stability (Mang, 2017).

CTO Derived Bio-oil

The bio-oil product is a derivative of TOR. The oil is easy flowing at ambient temperature and has desirable cold temperature properties. Table 4 details the characteristics.

Table 4: Properties of CTO derived bio-oil. See methodology section for ASTMs and units

Property	1000 Series	3000 Series
Kinematic Viscosity (40 °C)	45	22
Density at 20 °C	0.97	0.96
Color	12	2
Acid Value	8	3
Flash Point (COC)	145	142
Pour Point	-14	-24
Aniline Point	13	13

The aniline point (Table 5) of the bio-oil is indicative of its high solvency power. The K_B (Kauri-butanol value) of the oil is similar to that of methyl soyate. Table 5 lists the K_B values of common solvents for comparison with the bio-oil.

Table 5: Kauri-butanol values of common solvents

Solvents	K_B Value (ASTM D-1133)
Naphtha	34
Mineral Spirits	39
CTO derived bio-oil	58
Methyl Soyate	59
Cyclohexane	60
D-Limonene	67
Toluene	105

The material was tested as a carrier for a lubricating ester in the following WBM formulation (Table 6).

Table 6: WBM formulation. * = pounds per barrel, ** = pounds per gallon

11.5 ppg KCL Polymer WBM Formulation	
Sodium Bentonite	7 ppb*
Starch	4 ppb
Xanthan Gum	1 ppb
PAC LV	1.5 ppb
KCl	25 ppb
PHPA	0.4 ppb
Biocide (triazine)	0.1 ppb
Drill Solids (SEBC)	15 ppb
Barite	to 11.5 ppg**
Caustic Soda	to 9.5 pH

The lubricant was added at 3 v/v % to the above formulation (Table 6). The lubricant was 20:80 w/w % lubricating ester to carrier (e.g., bio-oil). The mud underwent EP lubricity testing and rheology testing (Figure 3 and Table 7, respectively). The carrier capability of the CTO based bio-oil was compared to an oil containing C_{8-26} isomers, defined as Competitor A, and an internal olefin oil, referred to as Competitor B. The samples were each added to the formulation shown in Table 6.

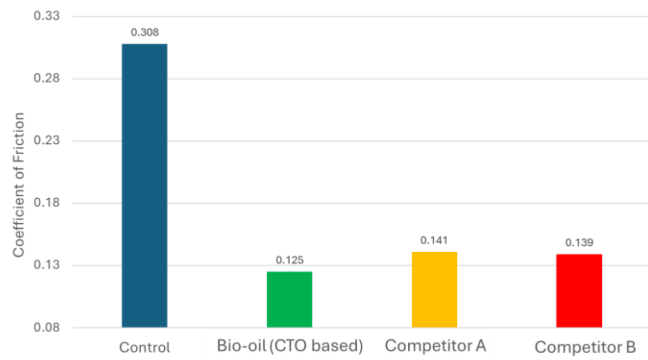

Figure 3: CoF from EP Lubricity Tester, (150 inch pounds, 60 rpm). No lubricant package in the control. Competitor A, C_{8-26}; Competitor B, internal olefin oil

The bio-oil provided a CoF comparable to Competitor A and Competitor B (Figure 3). A rheological analysis (Table 7) of the tested mud systems showed the bio-oil to have no harm to the system's rheology.

Table 7: Rheology of tested muds. No lubricant was in the control. Competitor A, C_{8-26}; Competitor B, internal olefin oil

	Control	Bio-Oil	Competitor A	Competitor B
Plastic Viscosity (cP @ 120 °F)	18	17	18	17
Yield Point (lb/100 ft^2)	29	30	29	30
10 s Gel Strength (lb/100 ft^2)	9	10	9	10
10 m Gel Strength (lb/100 ft^2)	13	14	13	11

Conclusion

The pine chemical industry plays a central role in upcycling forest-derived byproducts into high value, performance-driven materials used within the energy sector. CTO, a renewable byproduct of the Kraft pulping process, is refined to TOFA, TOR, DTO and pitch. TOFA stands out not only for its performance capabilities, but also for its link to responsible forestry and circular-economy principles thereby, giving customers a pathway to meet both performance expectations and sustainability commitments. With robust growth in the softwood pulp market and significant multimillion to billion dollar investments in mill and refinery capacity, these factors support confidence in the long-term resilience and reliability of the CTO supply chain. On top of this, CTO refiners are investing in their core assets and further innovating pine-based solutions thereby reinforcing the certainty in the future of pine chemicals. For customers, this means confidence in supply stability, in renewable sourcing, and in the broad chemical versatility enabled by CTO and its derivatives.

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Methodology

Kinematic viscosity – ASTM D-445, cSt
Density – ASTM D-1480, g/cm^3
Color – AQCM 002, Gardner
Acid Value – AQCM 001, mg KOH/g
Flash Point (COC) – ASTM D-92, °C
Pour Point – ASTM D-97, °C
Aniline Point – ASTM D-611, °C

References

Beaver, Ty. "Wallula Plant to Close Paper Machine Resulting in Loss of 200 Jobs." TriCities Area Journal of Business RSS, December 4, 2025. https://www.tricitiesbusinessnews.com/articles/pca-wallula-plant-to-cut-200-jobs.

"Comparison of Softwood Pulp and Hardwood Pulp." Paper Pulp Mill, July 18, 2018. https://paperpulpingmachine.com/softwood-pulp-and-hardwood-pulp-comparison/.

Den Otter, M. J. A. M. "The Clay-Catalysed Dimerisation of Oleic Acid," 1968.

Fengjiao Yi, Peng He, Huimin Chen, Yurong He, Zhichao Tao, Tao Li, Guoyan Zhao, Yifeng Yun, Xiaodong Wen, Yong Yang, and Yongwang Li. ACS Catalysis **2021** *11* (17), 11293-11304. DOI: 10.1021/acscatal.1c02846

Franklin, Savannah. "North American and European Containerboard Capacity Declines - Has Growth in the Sector Finally Reached Its Peak?" Fisher Insights, February 6, 2023. https://www.fisheri.com/blog/north-american-and-european-containerboard-capacity-declines-has-growth-in-the-sector-finally-reached-its-peak.

Forisk, August 28, 2025. https://forisk.com/wp-content/uploads/Press-Release_Mill-DB_20250828.pdf.

Mang, Theo, and Wilfried Dresel. *Lubricants and lubrication*. 3rd ed. Vol. 1. 2 vols. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA, 2017.

Paper Advance Editorial Team. "Smurfit Westrock Invests $65m in Corrugated Packaging in Sonora." Paper Advance, December 31, 2025. https://www.paperadvance.com/news/industry-news/smurfit-westrock-invests-65m-in-corrugated-packaging-in-sonora.html.

Parfenova LV, Bikmeeva AK, Kovyazin PV, Khalilov LM. The Dimerization and Oligomerization of Alkenes Catalyzed with Transition Metal Complexes: Catalytic Systems and Reaction Mechanisms. Molecules. 2024 Jan 19; DOI: 10.3390/molecules29020502

Phillips, April. "International Paper Launches Groundbreaking Construction of Massive Box Plant in Waterloo, Iowa." International Paper, May 22, 2025. https://www.internationalpaper.com/resources/article/groundbreaking-box-plant-iowa.

Pyzyk, Katie. "International Paper to Close 4 Facilities, Affecting 1,100 Employees." Packaging Dive, August 21, 2025. https://www.packagingdive.com/news/international-paper-two-mill-closures-riceboro-savannah-georgia-layoffs/758254/.

"The Future of Packaging: Corrugated Box Market Set to Soar beyond $800 Billion by 2034 - Korpack - Packaging Solutions for Complex Businesses." Korpack, January 13, 2025. https://korpack.com/the-future-of-packaging-corrugated-box-market-set-to-soar-beyond-800-billion-by-2034/.

Wade, L G. *Organic Chemistry*. 8th ed. Glenview, IL: Pearson, 2013.

"What Are Forest Management Practices?" American Forest & Paper Association | AF&PA, October 8, 2024. https://www.afandpa.org/news/2024/what-are-forest-management-practices.

White, Erik. "Domtar Says Northern Ontario Paper Mill to Shut down 'Indefinitely.'" CBC News, September 6, 2023. https://www.cbc.ca/news/canada/sudbury/domtar-espanola-paper-mill-northern-ontario-shut-down-1.6958072.