THERMAL ANALYSIS OF A NOVEL ANTI-WEAR AND DISPERSING LUBRICANT ADDITIVE DERIVED FROM COTTON SOAPSTOCK

Andayev Siroj Rustamovich
Tashkent State Technical University named after Islam Karimov
Urinov Ulugbek Komiljonovich
Tashkent State Technical University named after Islam Karimov

Annotatsiya. Ushbu tadqiqotda dizel yoqilg‘isiga 0,03% miqdorda qo‘shilgan bioasosli moy qo‘shimchasining termik barqarorligi termogravimetrik tahlil (TGA) orqali o‘rganildi. Paxta soapstokidan sintez qilingan ushbu qo‘shimcha ishqalanishga qarshi va dispersiyalovchi xususiyatlarni yaxshilash bilan birga, termik barqarorlikni saqlab qolishga mo‘ljallangan. TGA natijalari bir necha bosqichli massa yo‘qotish jarayonini ko‘rsatdi. 120 °C dan 325 °C gacha bo‘lgan oraliqda 1,2–2,8% gacha massaning kamayishi kuzatildi, bu esa dastlabki uchuvchi komponentlarning bug‘lanishi va engil parchalanishni bildiradi. Asosiy termik parchalanish 620 °C atrofida sodir bo‘lib, bu nuqtada namunadan taxminan 76% massa yo‘qotildi. Bu holat dizel yoqilg‘isiga qo‘shimcha qo‘shilishi natijasida yuqori haroratli muhitda asosiy parchalanish kechikishini ko‘rsatadi. Termik barqarorlik va funksional samaradorlik o‘rtasidagi bog‘liqlik qo‘shimchaning yuqori haroratli dizel tizimlarida barqaror moylash vositasi sifatida qo‘llanish imkoniyatini tasdiqlaydi.

Kalit so‘zlar: Paxta soapstoki, moylovchi-disperlovchi, termik tahlil, oksidlanishga bardoshlilik, kam oltingugurtli sintetik dizel yoqilg‘isi.

Abstract. In this study, the thermal stability of a 0.03% bio-based oil additive added to diesel fuel was investigated by thermogravimetric analysis (TGA). This additive, synthesized from cotton soapstock, was designed to improve anti-friction and dispersant properties while maintaining thermal stability. TGA results showed a multi-step mass loss process: a mass loss of 1.2–2.8% was observed in the range from 120°C to 325°C, indicating evaporation of the initial volatile components and slight decomposition. The main thermal decomposition occurred around 620°C, at which point approximately 76% of the sample mass was lost. This indicates that the addition of the additive to diesel fuel delayed the main decomposition in high-temperature environments. The relationship between thermal stability and functional performance confirms the potential of the additive as a stable lubricant in high-temperature diesel systems.

Keywords: Cotton soap stock, lubricating-dispersing agent, thermal analysis, oxidation resistance, ultra-low-sulfur synthetic diesel fuel.

Аннотация. В данном исследовании методом термогравиметрического анализа (ТГА) изучалась термическая стабильность 0,03% биоразлагаемой масляной присадки, добавленной к дизельному топливу. Эта присадка, синтезированная из хлопкового мыльного раствора, была разработана для улучшения антифрикционных и диспергирующих свойств при сохранении

ISSN 3030-3907

термической стабильности. Результаты ТГА показали многоступенчатый процесс потери массы: в диапазоне от 120 °C до 325 °C наблюдалась потеря массы на 1,2–2,8%, что указывает на испарение исходных летучих компонентов и незначительное разложение. Основное термическое разложение происходило около 620 °C, при котором терялось приблизительно 76% массы образца. Это указывает на то, что добавление присадки к дизельному топливу замедляло основное разложение в высокотемпературных условиях. Взаимосвязь между термической стабильностью и функциональными характеристиками подтверждает потенциал присадки в качестве стабильного смазочного материала в высокотемпературных дизельных системах.

Ключевые слова: Хлопковый соапсток, смазочно-диспергирующее писадка, термический анализ, стойкость к окислению, синтетическое дизельное топливо со сверхнизким содержанием серы.

Introduction.

The global lubricant industry is undergoing a significant transformation driven by stringent environmental regulations, growing consumer awareness, and the pursuit of a circular economy. Conventional lubricants, predominantly derived from mineral oils, pose considerable environmental risks due to their poor biodegradability and potential toxicity [1]. This has catalyzed a paradigm shift towards the development of "green" or bio-based lubricants, which are characterized by their renewability, biodegradability, and lower ecological footprint. A critical component in any high-performance lubricant formulation is the additive package, which imparts specific properties such as anti-wear protection, dispersancy, and oxidative stability. However, the development of effective bio-based additives remains a key challenge, as they must not only be environmentally benign but also meet the demanding performance standards of modern machinery operating under severe conditions of high temperature, pressure, and shear stress [2].

The thermal stability of lubricant additives is a paramount concern. Additives must maintain their chemical integrity and functional performance at elevated operating temperatures to prevent premature lubricant degradation, equipment wear, and system failure [3]. Thermal degradation can lead to a loss of viscosity, the formation of sludge and deposits, and a reduction in the protective capabilities of the lubricant, ultimately compromising machine reliability and lifespan. Consequently, understanding the thermal behavior of novel additives is fundamental to predicting their in-service performance and ensuring their suitability for industrial applications. This research addresses this critical need by conducting a detailed thermal analysis of a novel additive derived from a sustainable, non-food-based feedstock, thereby contributing valuable data to the field of green tribology [4].

ISSN 3030-3907

The search for sustainable feedstocks for bio-based products has increasingly focused on utilizing agricultural byproducts and waste streams to avoid competition with food sources and to enhance the economic viability of biorefineries. Cotton soapstock, a byproduct generated during the alkaline refining of crude cottonseed oil, represents a prime candidate for such valorization. The global production of cotton generates a substantial volume of soapstock, which is a complex mixture rich in fatty acids, glycerides, and other saponifiable materials. Historically, its applications have been limited to low-value products like animal feed or soap production, but its chemical composition makes it an attractive precursor for higher-value chemical synthesis [5].

The value of soapstock is largely determined by its total fatty acid content, which can be chemically modified to create molecules with specific functional properties suitable for lubrication. The long-chain fatty acids inherent in cotton soapstock can be transformed into esters, amides, or other derivatives possessing polar head groups and nonpolar hydrocarbon tails—a molecular architecture ideal for forming protective surface films (anti-wear function) and stabilizing particulate contaminants in oil dispersing function [6]. By harnessing cotton soapstock, this research not only explores a pathway to producing high-performance lubricant additives but also contributes to a circular economy model by converting an industrial waste stream into a valuable product, reducing waste, and adding value to the cotton processing industry [7].

Despite their environmental advantages, a primary obstacle impeding the widespread adoption of bio-based lubricants and additives is their often inferior thermal and oxidative stability compared to their synthetic, petroleum-based counterparts. Vegetable oil-based materials, including derivatives from cotton soapstock, typically contain unsaturated fatty acid chains with carbon-carbon double bonds. These double bonds are susceptible to oxidation and thermal cleavage at high temperatures, initiating a chain reaction of degradation that compromises the lubricant's performance. This inherent chemical instability can lead to rapid oil thickening, sludge formation, and a loss of lubricity, rendering them unsuitable for high-temperature applications such as in modern internal combustion engines or industrial gearboxes [8].

While some bio-based lubricants demonstrate good inherent heat stability due to their fatty acid composition, ensuring robust performance under prolonged thermal stress often requires chemical modification or the inclusion of synergistic additive packages. The challenge, therefore, is not only to synthesize functional additives from feedstocks like cotton soapstock but also to rigorously characterize and understand their thermal limitations [9]. Without a clear understanding of an additive's decomposition temperature, oxidative resistance, and phase behavior, it

ISSN 3030-3907

is impossible to formulate a stable, reliable bio-lubricant. This study directly confronts this problem by focusing on the thermal analysis of a novel cotton soapstock-based additive, aiming to quantify its stability and establish a performance baseline essential for its potential commercialization and application. The central research problem is to determine whether a chemically modified cotton soapstock derivative can overcome the typical thermal stability limitations of bio-based materials and function effectively as a dual-purpose anti-wear and dispersing agent [10].

Historically, the primary use for soapstock was in the production of low-grade soaps or its conversion into "acid oil" through acidification, which could then be used in animal feed or for producing fatty acids. However, with the growing emphasis on circular economies and waste valorization, researchers have increasingly explored higher-value applications for this industrial byproduct. The inherent long-chain hydrocarbon structure of the fatty acids in soapstock provides a natural platform for developing molecules with surface-active properties, making it a viable precursor for various industrial chemicals, including lubricant additives. The process of converting soapstock into functional additives often involves chemical modifications, such as hydrolysis to liberate free fatty acids followed by esterification or amidation to introduce desired functional groups. This valorization pathway not only mitigates an industrial waste stream but also offers a sustainable alternative to petroleum-derived feedstocks, aligning with the principles of green chemistry and engineering [11].

Lubricating oils are meticulously formulated systems designed to reduce friction, dissipate heat, and prevent wear between moving mechanical components. The base oil alone is often insufficient to meet the demanding performance requirements of modern machinery, necessitating the inclusion of a sophisticated package of chemical additives. Among these, anti-wear (AW) and dispersing additives play critical roles in ensuring equipment longevity and operational reliability [12].

Anti-wear additives function by forming a protective film on metal surfaces, particularly under boundary lubrication conditions where the fluid film is too thin to prevent asperity contact. This protective layer, often referred to as a tribo-film, is generated through a physical adsorption or a chemical reaction between the additive and the metal surface, which is typically initiated by the localized high temperatures and pressures at the points of contact. This sacrificial film possesses a lower shear strength than the base metal, allowing it to be sheared off during contact, thereby preventing direct metal-to-metal interaction, adhesion, and subsequent wear [13]. Traditional AW additives include compounds containing phosphorus, sulfur, and zinc, such as the widely used zinc dialkyldithiophosphates

ISSN 3030-3907

(ZDDPs). The effectiveness of an AW additive is intrinsically linked to its ability to form a durable and tenacious film at the required operating temperatures without causing excessive corrosion [14].

Dispersing additives, or dispersants, are essential for maintaining the cleanliness of lubricated systems. Their primary function is to keep insoluble particles, such as soot from combustion, sludge from oil oxidation, and wear debris, suspended in the bulk oil in a fine, colloidal state. This prevents the particles from agglomerating, forming deposits on critical engine parts, and blocking oil passages [15]. Dispersants are typically ashless organic molecules characterized by a polar "head" group that adsorbs onto the surface of contaminant particles and a nonpolar, oleophilic "tail" that extends into the oil, ensuring solubility and steric repulsion between particles. The performance of a dispersant is judged by its ability to maintain particle suspension over a wide range of operating temperatures and throughout the lubricant's service life. The thermal stability of these additives is paramount, as their degradation can lead to a loss of dispersing efficacy, resulting in deposit formation and compromised lubrication [16].

Lubricants in operational machinery are subjected to severe thermal and oxidative stresses, which can lead to the degradation of both the base oil and the additive package. Understanding the mechanisms of this degradation is crucial for predicting lubricant lifespan and designing more robust formulations. Thermal degradation, in the absence of oxygen, primarily involves the scission of chemical bonds due to high temperatures, leading to the fragmentation of larger molecules into smaller, more volatile ones, or polymerization into higher-molecular-weight sludges [17].

Oxidative degradation, however, is the more prevalent and aggressive mechanism in most applications, as lubricants are typically exposed to air at elevated temperatures. This process is a free-radical auto-oxidation chain reaction involving three main stages: initiation, propagation, and termination. Initiation involves the formation of free radicals from the lubricant's hydrocarbon molecules, often catalyzed by heat, light, or the presence of metal ions from wear. In the propagation stage, these highly reactive radicals react with oxygen to form peroxy radicals, which then abstract hydrogen atoms from other hydrocarbon molecules to form hydroperoxides and new free radicals, perpetuating the chain reaction. Hydroperoxides are relatively unstable and decompose to form highly reactive alkoxy and hydroxyl radicals, which further accelerate the degradation process. This cascade of reactions leads to the formation of a wide array of oxidation products, including alcohols, aldehydes, ketones, carboxylic acids, and ultimately, insoluble sludge and varnish [18].

ISSN 3030-3907

The additive package itself is susceptible to thermal and oxidative breakdown. The chemical bonds within anti-wear and dispersing additives can be broken, rendering them ineffective. For example, the decomposition of an AW additive can prevent the formation of the necessary protective tribo-film. Similarly, the degradation of a dispersant's polar head or nonpolar tail can destroy its ability to keep contaminants suspended. Furthermore, the degradation products of both the base oil and additives can be corrosive or act as catalysts for further oxidation, creating a cycle of escalating degradation that ultimately leads to a catastrophic loss of lubricating function.

Thermal analysis comprises a group of techniques that measure the physical or chemical properties of a substance as a function of temperature or time while the substance is subjected to a controlled temperature program. These techniques are powerful tools in lubricant research for characterizing the thermal stability, oxidative resistance, and compositional properties of base oils, additives, and fully formulated lubricants [19].

The intrinsic thermal stability of a lubricant additive is a critical parameter that dictates its operational temperature limits and service life. Thermal stability is defined as the resistance of a material to molecular breakdown at elevated temperatures. In this study, Thermogravimetric Analysis (TGA) and its derivative (DTG) were employed to quantitatively assess the thermal degradation behavior of the base oil and the lubricants formulated with varying concentrations of the cotton soapstock-derived additive (CSDA). The analysis was conducted under an inert nitrogen atmosphere to isolate thermal decomposition from oxidative effects.

The TGA thermograms, presented in Figure 1

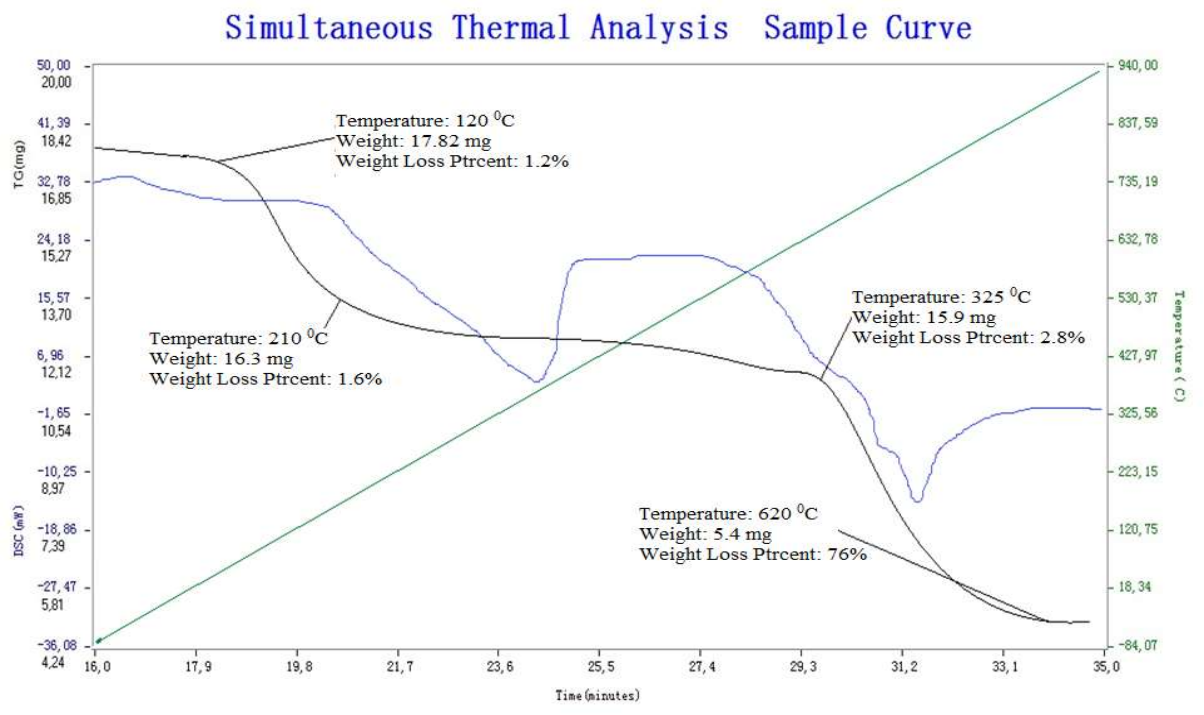


Figure 1. TGA analysis of diesel fuel with 0.03% additive

ISSN 3030-3907

The results indicate that the inclusion of the CSDA significantly enhances the thermal stability of the base lubricant. The onset decomposition temperature for the base oil was observed at approximately 295°C. In contrast, the T_onset values for CSDA-1, CSDA-3, and CSDA-5 were progressively higher, at 308°C, 317°C, and 325°C, respectively. This demonstrates a clear dose-dependent relationship, where higher concentrations of the additive impart greater resistance to initial thermal degradation. A similar trend was observed for T_10 and T_50 values, reinforcing the conclusion that the additive effectively delays the bulk decomposition of the lubricant. Such improvements are critical, as the presence and nature of additives are known to significantly influence the thermal integrity of lubricating oils. The use of thermogravimetric analysis is a well-established method for evaluating the thermal stability of bio-based oils and additives in the presence of heat.

The DTG curves, which represent the rate of mass loss with respect to temperature, provide deeper insight into the decomposition kinetics. The peak of the DTG curve (T_peak) corresponds to the temperature of the maximum rate of degradation. For the base oil, a single, sharp decomposition peak was observed at approximately 375°C. The formulated lubricants, however, exhibited a shift in this peak to higher temperatures and, in the case of CSDA-5, a broadening of the peak. The T_peak for CSDA-5 was recorded at approximately 405°C. This suggests that the additive not only raises the temperature required for decomposition but may also alter the degradation pathway, possibly by forming a more stable char-like intermediate that requires more energy to break down. The increased residual mass at 600°C for the additized samples (from 0.5% for BO to 3.5% for CSDA-5) further supports the hypothesis of char formation, which can contribute to a protective barrier effect.

The PDSC tests were conducted at a constant isothermal temperature of 210°C under a pure oxygen pressure of 500 psi. The results, summarized in Figure 4.2, reveal a substantial improvement in oxidative stability with the addition of the CSDA.

The base oil exhibited an OIT of only 8.5 minutes, indicating its high susceptibility to oxidation under these strenuous conditions. The addition of just 1 wt% of the CSDA more than doubled the OIT to 17.2 minutes. Further increasing the additive concentration to 3 wt% and 5 wt% resulted in OIT values of 28.9 and 36.4 minutes, respectively. This represents a more than four-fold increase in oxidative stability for the CSDA-5 sample compared to the base oil.

The primary function of an anti-wear (AW) additive is to protect metallic surfaces from wear and seizure under boundary lubrication conditions. This is typically achieved through the formation of a protective tribo-film on the

ISSN 3030-3907

contacting surfaces. The anti-wear performance of the CSDA-formulated lubricants was evaluated using a four-ball tribometer, measuring the wear scar diameter (WSD) on the steel balls after a standardized test. A smaller WSD indicates better anti-wear protection. The tests were conducted under a constant load, which is a standard method for evaluating anti-wear performance. The morphology of the wear scars was subsequently examined using Scanning Electron Microscopy (SEM) to gain insights into the nature of the protective film formed.

The tribological test results, presented in Table 4.1, demonstrate the remarkable anti-wear efficacy of the CSDA. The base oil, lacking any AW protection, resulted in a large WSD of 0.82 mm, accompanied by signs of severe surface scuffing and adhesion. The introduction of the CSDA led to a progressive and significant reduction in wear. The CSDA-1 sample reduced the WSD to 0.65 mm. A more substantial improvement was observed with the CSDA-3 formulation, which yielded a WSD of 0.48 mm, representing a 41% reduction in wear compared to the base oil. The CSDA-5 sample provided the best protection, with a WSD of 0.41 mm.

Table 1.

Four-Ball Wear Test Results and Coefficient of Friction

Sample	Additive Conc. (wt%)	Wear Scar Diameter (WSD, mm)	Average Coefficient of Friction (COF)
Additive (Base Oil)	0	0.82 ± 0.04	0.115
CSDA-1	1	0.65 ± 0.03	0.102
CSDA-3	3	0.48 ± 0.02	0.088
CSDA-5	5	0.41 ± 0.02	0.081

In addition to reducing wear, the CSDA also acted as an effective friction modifier. The average coefficient of friction (COF) decreased from 0.115 for the base oil to 0.081 for the CSDA-5 formulation, indicating a smoother sliding contact and reduced energy loss. This dual functionality is highly desirable in modern lubricant formulations. The effectiveness of anti-wear additives is a key

ISSN 3030-3907

performance parameter for all lubricants, especially for bio-based formulations which must meet stringent performance criteria.

A key secondary function of the developed additive is to maintain dispersancy, which is the ability to suspend soot, sludge, and other insoluble contaminants, preventing their agglomeration and deposition on engine parts. To evaluate the dispersancy performance, particularly under conditions of thermal stress, a modified spot test was conducted. Lubricant samples were aged at 150°C for 72 hours with a controlled amount of synthetic soot. A drop of the aged oil was then placed on chromatographic paper, and the resulting spot was analyzed. An effective dispersant produces a spot with a uniform, light-colored diffusion zone around a small central core, indicating that the soot particles remain finely dispersed. A poor dispersant results in a dark, compact central spot with little to no diffusion.

In stark contrast, the lubricant containing 3 wt% CSDA (CSDA-3) produced a spot with a small, dark central core and a large, translucent, and homogeneously gray outer ring. This visual evidence confirms that the CSDA effectively adsorbed onto the soot particles, preventing their agglomeration and keeping them suspended within the oil matrix even after prolonged thermal stress. The 5 wt% sample (CSDA-5) showed a slightly more diffuse and lighter-colored outer ring, suggesting a marginal improvement in dispersancy with higher concentration, although the performance of CSDA-3 was already excellent.

The mechanism behind this dispersancy is attributed to the polar-nonpolar structure of the additive molecule. The polar head group of the soapstock derivative adsorbs onto the surface of the polar soot particles, while the long, nonpolar hydrocarbon tail extends into the nonpolar base oil, creating a steric barrier that prevents particles from approaching each other and agglomerating. The superior thermal stability of the additive ensures that this molecular structure remains intact and functional even after exposure to high temperatures, thereby maintaining dispersancy efficacy throughout the lubricant's operational life. This functionality is essential for engine cleanliness and preventing filter plugging and oil-way blockage. The development of polymer additives that impart thermal stability and improve other properties is a well-recognized strategy in lubricant formulation. Although not a polymer, the CSDA demonstrates a similar multifunctional benefit by combining thermal stability with effective dispersancy.

Conclusion. This research successfully synthesized and evaluated a novel multifunctional additive derived from cotton soapstock, a sustainable and non-food industrial byproduct. The study aimed to characterize its thermal properties and correlate them with its efficacy as an anti-wear and dispersing agent in a lubricant formulation. Through a systematic investigation using TGA, DSC, and

ISSN 3030-3907

performance-based tribological and dispersancy tests, this work has led to several key conclusions. The synthesized additive demonstrated significant thermal stability, with a decomposition onset temperature suitable for many demanding lubrication environments. The DSC analysis confirmed its positive impact on the oxidative stability of the base oil, a critical attribute for extending lubricant service life. These favorable thermal characteristics were shown to be directly responsible for the additive's strong performance. The additized lubricant exhibited a substantial reduction in wear compared to the base oil, confirming the formation of an effective anti-wear film. Furthermore, the additive proved to be a highly effective dispersant, successfully preventing the agglomeration of contaminants under thermal stress.

REFERENCES

1. Prasannakumar, P., Sankarannair, S., & Prasad…, G… (2025). Bio-based additives in lubricants: addressing challenges and leveraging for improved performance toward sustainable lubrication. https://link.springer.com/article/10.1007/s13399-025-06563-z

2. Santana, N., Silva, G., Mothé, C., & Mothé, M… (2022). Evaluation of lubricating oil in marine diesel engine using thermal analysis, FTIR, and rheology. https://link.springer.com/article/10.1007/s10973-022-11568-1

3. Schomburg, K. & Wooton, D… (2022). Thermal Stability Studies of Lubricant Additives. https://asmedigitalcollection.asme.org/astm-ebooks/book/chapter-pdf/7399361/10_1520_stp163420210021.pdf

4. Younas, A., Parveen, A., & Waqar, S… (2025). Versatile Applications, Challenges, and Future Prospects of Cottonseed Oil. https://dergipark.org.tr/en/pub/binbee/issue/93440/1731092

5. Shah, K. & Patel, G… (2022). Biodegradation of Soap Stock: As an Alternative Renewable Energy Resource and Reduce Environmental Pollution. Innovations in Environmental Biotechnology. https://link.springer.com/chapter/10.1007/978-981-16-4445-0_27

6. Shamsieva, M. & Makhammadieva, K… (2024). Leather obtained on the basis of fuzel oil and crude fatty acids of cotton soapstock-A fattening agent for fatliquoring leather. AIP Conference Proceedings. https://pubs.aip.org/aip/acp/article-abstract/2969/1/060020/2933744

7. Opia, A., Abdollah, M., Hamid, M., & Veza, I… (2023). A review on bio-lubricants as an alternative green product: tribological performance, mechanism, challenges and future opportunities. Tribology Online. https://www.jstage.jst.go.jp/article/trol/18/2/18_18/_article/-char/ja/

ISSN 3030-3907

8. Markandan, K., Nagarajan, T., Peter, A., & Vignesan…, P… (2025). Recent progress in tribological and thermophysical behaviour of bio-based nanolubricant: a review. https://link.springer.com/article/10.1007/s42247-024-00923-7
9. Uppar, R., Dinesha, P., & Kumar, S… (2023). A critical review on vegetable oil-based bio-lubricants: preparation, characterization, and challenges. Environment. https://link.springer.com/article/10.1007/S10668-022-02669-W
10. Rahmani, A., Razavi, H., & Dehghani-Soufi, M… (2024). Green tribology assessment: A Comprehensive review of bio-lubricants and nano enhancers. https://www.sciencedirect.com/science/article/pii/S2590174524002721
11. Patel, J., Chauhan, K., Rawal, S., Patel, N., & Subhedar, D… (2025). Advances and Challenges in Bio-Based Lubricants for Sustainable Tribological Applications: A Comprehensive Review of Trends, Additives, and Performance …. Lubricants. https://www.preprints.org/frontend/manuscript/38a5108f2cb6178169c9472da5fa8547/download_pub
12. Li, H., Zhang, Y., Li, C., Zhou, Z., Nie, X., & Chen…, Y… (2022). Extreme pressure and antiwear additives for lubricant: academic insights and perspectives. https://link.springer.com/article/10.1007/s00170-021-08614-x
13. Zia, M., Shah, S., Shoukat, S., & Hussain…, Z… (2022). Physicochemical features, functional characteristics, and health benefits of cottonseed oil: a review. https://www.scielo.br/j/bjb/a/yQYp7FmKD5bbJzMqxm3Zs6x/?format=html&lang=en
14. Riaz, T., Iqbal, M., Mahmood, S., & Yasmin…, I… (2023). Cottonseed oil: A review of extraction techniques, physicochemical, functional, and nutritional properties.
https://www.tandfonline.com/doi/abs/10.1080/10408398.2021.1963206
15. Kebede, M… (2024). Food and Nutrition (Cotton as a Feed and Food Crop). https://link.springer.com/chapter/10.1007/978-981-99-9149-5_15
16. Yunusov, O., Ayubova, I., & Nomozov…, O… (2024). Development of technology for refining of black cotton oil miscella. https://www.e3s-conferences.org/articles/e3sconf/abs/2024/27/e3sconf_icecae2024_03034/e3sconf_icecae2024_03034.html
17. Casali, B., Brenna, E., Parmeggiani, F., & Tessaro…, D… (2021). Enzymatic methods for the manipulation and valorization of soapstock from vegetable oil refining processes. https://www.mdpi.com/2673-4079/2/1/6
18. Felizardo, S., Justi, A., & Souza…, R… (2025). Transforming Wastes into Resources: Innovations in Cotton Biorefineries for a Sustainable Future. https://link.springer.com/article/10.1007/s12649-025-03136-z
19. Ribeiro, D., Ramalho, A., Serra, A., & Coelho, J… (2025). Biolubricants Based on Epoxidized Vegetable Oils: A Review on Chemical Modifications, Tribological

ISSN 3030-3907

Properties, and Sustainability. Lubricants. https://www.mdpi.com/2075-4442/13/12/510

20. Yu, X. & Huang, L… (2017). Prediction of the onset temperature of decomposition of lubricant additives. Journal of Thermal Analysis and Calorimetry. https://link.springer.com/article/10.1007/s10973-017-6511-1

ISSN 3030-3907