Jurnal Tribologi 47 (2025) 249-297

MYTRIBOS
Malaysian Tribology Society

Jurnal Tribologi

Website : jurnaltribologi.mytribos.org e-issn: 2289-7232

Multi-objective optimization of Botryococcus Braunii based bio-nanolubricant formulations doped with hybrid nano-additives using the MULTIMOORA method

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KEYWORDS

Bionanolubricant
MULTIMOORA method
Tribological properties
Physiochemical properties
Ratio analysis

ABSTRACT

The lubricating oil industry plays a key role in improving the efficiency and durability of mechanical and automotive systems. This study uses a multi-objective optimization method to find the best bio-nanolubricant made from Botryococcus braunii algae oil, Oleic acid as surfactant, and hybrid nano-additives. Several samples were tested for important properties like viscosity, flash point, acid value, friction coefficient, and wear rate. The objective of this study is to find a formulation that balances performance and reliability. The MULTIMOORA method is deployed due to its robustness in handling conflicting criteria well without bias and its independence from normalization and weighting biases by comprising the ratio analysis, reference point analysis and the full multiplicative form. Attributes of each sample are ranked and normalized through this framework to ascertain an objective selection. This analytical methodology offers a reliable decision-making strategy for the lubricant formulation and selection in multi-criteria environments. This method ranked each sample using nine key attributes density, kinematic viscosity, flash point, pour point, cloud point, acid value, friction coefficient, wear and specific wear rate. Our results show that adding graphene oxide and MWCNTs improves wear and friction resistance. The MULTIMOORA optimized formulation, B99O1G0.5C0.5, demonstrated stronger stability, lower friction, and less wear. It outperformed commercial 20W-40 oil, offering better wear resistance and thermal stability, making it suitable for demanding mechanical uses. This is the first study to apply MULTIMOORA for optimizing bio-nanolubricants and provides a reliable approach for multi-criteria lubricant selection.

Received 15 August 2025; received in revised form 11 October 2025; accepted 29 October 2025.
To cite this article: Singh and Chauhan (2025). Multi-objective optimization of Botryococcus Braunii based bio-nanolubricant formulations doped with hybrid nano-additives using the MULTIMOORA method. Jurnal Tribologi 47, pp.249-297.

1.0 INTRODUCTION

Lubricating oil, derived from crude oil, contains high-molecular-weight paraffins, naphthenes, and aromatics. It reduces friction, wear, and corrosion in engines and machinery while aiding heat dissipation and sealing. Demand for lubricating oils including mineral, synthetic, semi-synthetic, and biodegradable types is rising, especially in Asia and China due to rapid industrial and automotive growth. However, lubricating oil degrades during use because of oxidation, thermal stress, and contamination from metal particles, moisture, additives, and combustion by-products like SOx and NOx, which form acids that cause corrosion. Around 24 million metric tons of waste lubricating oil (WLO) are discarded yearly, creating environmental threats due to toxic metals, polycyclic aromatic hydrocarbons (PAHs), and hydrocarbon residues. Improper disposal can contaminate soil and water and release harmful vapors [1].

Several re-refining techniques like acid/clay treatment, solvent extraction, vacuum distillation, and adsorption recover base oils from WLO. While acid/clay treatment is common, it generates hazardous sludge. Cleaner options like solvent extraction and adsorption using materials like activated carbon, clay, and agricultural waste can remove heavy metals and PAHs more safely. Besides re-refining, WLO can be repurposed for energy production, biodiesel, or reused as base oil, though issues with cost, quality consistency, and toxic byproducts remain [1]. The foundations of tribology the science of friction, wear, and lubrication can be traced to Leonardo da Vinci (1452–1519). His work, found in the Codex Madrid I and Codex Atlanticus, detailed bearing design, wear, and lubricant use. While early research focused on friction, newer studies by Betancourt-Parra and Sawyer highlight Leonardo's insights into wear in practical systems like grinding and wooden shafts. His tribological ideas still influence modern mechanical systems [2], including those using waste-based lubricants. Greases are semi-solid lubricants made from base oil, thickener, and additives. They offer strong friction, wear, and heat reduction, corrosion protection, and noise dampening. This is especially vital in automotive systems. As electric vehicles (EVs) are projected to reach 30% of global vehicle sales by 2030, their high-speed motors and electric discharges demand greases with excellent thermal and electrical stability often based on synthetic oils. Still, biodegradable vegetable oils are becoming more popular due to environmental and cost concerns.

Common thickeners like lithium soaps are being replaced by alternatives like PTFE for better high-temperature performance. Studies comparing greases made from vegetable-based trimethylolpropane trioleate (TMPO) and synthetic perfluoropolyether (PFPE), both thickened with PTFE, show promising results for EVs [3]. Engine oils are essential in reducing friction, preventing corrosion, and managing heat. Their viscosity depends on hydrocarbon chain length, and they often contain additives like calcium, phosphorus, and zinc. Over time, exposure to oxidation, heat, and combustion residues alters oil properties such as viscosity, acid number, flash point, and specific gravity. Monitoring these changes ensures timely replacement and engine protection. A study in Pakistan showed how mineral oil properties degrade over various mileage intervals, highlighting the importance of quality control [4] and linking to global WLO challenges [1]. In wheel bearings, especially under high loads, grease is critical for reducing wear and friction. Its sticky consistency ensures long-term lubrication. Grease properties like base oil viscosity, thickener type, and flow behavior influence friction torque and bearing life. To meet BS6 and EV efficiency standards, low-friction greases with synthetic base oils and calcium or polyurea thickeners are favored. Bearing lubrication involves initial grease churning and oil bleeding, both crucial. While grease channeling is often studied through temperature profiles, its performance under electrohydrodynamic lubrication (EHL) conditions needs more research [5], especially for next-generation EV applications [3]. EV development, which started in the early 1800s, advanced significantly after the Toyota Prius launch in 1997. With growing global adoption of EVs due to climate and tech concerns, there is increased demand for lubricants and greases suited to EV-specific tribological challenges [6], supporting efforts to create sustainable lubricants from vegetable and waste oils [3, 7]. Replacing engine oil due to consumption increases maintenance costs. If oil is consumed excessively, it can shorten oil change intervals and lead to more engine deposits. Lubricating oil can also increase engine-out emissions especially HC, CO (in smaller engines), and particulate matter (PM), including both total mass and particle number. Most of the ash buildup in diesel particulate filters (DPFs) comes from consumed lubricating oil. High oil consumption leads to faster ash accumulation, requiring larger DPFs, more frequent regeneration (which affects fuel economy), and risks of ceramic substrate damage. Excess oil-based hydrocarbons in the DPF can cause uncontrolled regeneration, damaging the filter. Emission control catalysts like Diesel Oxidation Catalyst (DOC) and Selective Catalytic Reduction (SCR) must be designed to handle oil-derived poisons and hydrocarbons, which reduce their efficiency. While manufacturers aim for low oil consumption, achieving it consistently is challenging. Issues in engine design, material selection, manufacturing quality, or unexpected operating conditions can lead to high oil use even if not directly related to lubrication.

In some systems, manufacturers intentionally inject small amounts of oil into the fuel to extend oil change intervals and reduce service costs. This automatic oil replenishment system is limited under US 2007+ emission standards for heavy-duty diesel engines. Given environmental concerns and oil scarcity, researchers are turning to used oil (UO), including used engine oil (UEO) and used transformer oil (UTO), for grease production. Although considered hazardous waste, UO has value if properly treated. Malaysia generates about 150 million liters of UO annually, but UTO remains underused. Studies show greases made from UEO and UTO, with thickeners like sodium stearate, red gypsum, and fumed silica, plus additives like PTFE, graphite, and MoS_2, can meet performance standards. These support circular economy goals and reduce environmental harm [7], tying back to broader WLO recycling efforts [1] and green lubricant technologies [3]. Oxidation resistance is a key indicator of lubricant durability. Under thermal and mechanical stress, oils form reactive products like peroxides, alcohols, aldehydes, and acids, which may polymerize into sludge or varnish degrading performance and increasing wear. Techniques such as cyclic voltammetry, infrared spectroscopy, total acid/base number measurement, the rotating oxygen bomb test, and sludge analysis help assess oxidation stability. These methods are essential for developing robust lubricants for harsh conditions [8], especially those made from recycled oils and advanced nanotechnology [1, 7]. Figure 1 represents the market share distribution of various types of lubricating oils used for lubrication applications, highlighting the relative usage percentages of mineral oils, synthetic oils, bio-based oils, and other specialized lubricants across industrial and automotive sectors.

1.1 Lubricant

Lubricating oil is recognized as a critical component in reducing friction and wear in machinery. However, its disposal is hazardous due to toxic by-products like PAHs, sulfated ash, and heavy metals, making proper re-refining essential for environmental safety and circular economy goals [1]. Global consumption exceeds 40 million metric tons annually, with rising demand in the automotive, industrial, and marine sectors [1]. Improper disposal affects about 50% of used oil, often released into the environment untreated [4]. Sustainable techniques for re-refining include acid-clay treatment, solvent extraction, vacuum distillation, hydrofinishing, and membrane separation, which help restore vital oil properties such as viscosity index, pour point, flash point, and oxidation stability [1]. Among them, the MRD solvent process using N-methyl-2-pyrrolidone has shown superior base oil recovery with minimal catalyst poisoning [1]. Advanced analysis techniques such as FTIR, GC-MS, AAS, and TGA are used to evaluate the chemical composition, metal content, and thermal stability of recycled oil [1]. Leonardo da Vinci's early studies on lubrication, sliding contacts, and wear prediction laid the foundation for modern tribological understanding, centuries ahead of his time [2].

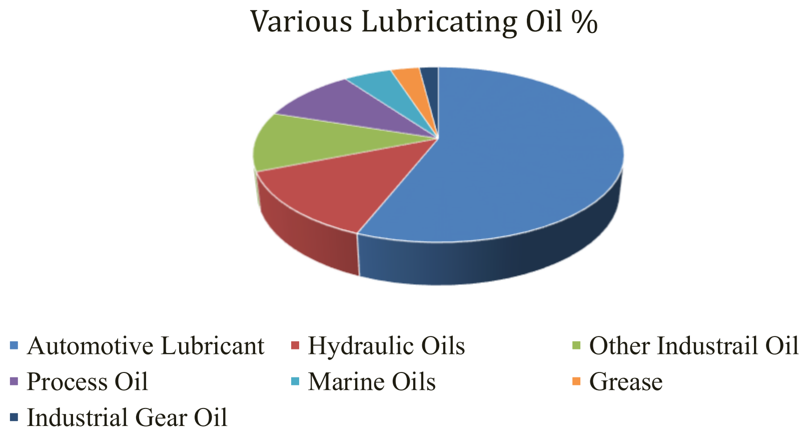

Figure1: Percentage of various lubricating oils used in market for lubrication.

Modern enhancements include using nano-additives like metal oxides and graphene to improve lubrication, reduce friction, and enhance oxidation stability, although high-cost limits widespread use [1]. Bio-based greases such as TMPO, thickened with PTFE, show promise for EVs due to 8.8% better thermal stability and 22.1% friction reduction under non-electric conditions, although PFPE performs better in wear resistance without current [3]. Similarly, grease formulated from treated used transformer and engine oils using additives like graphite, MoS_2, and PTFE, displayed excellent tribological properties, with graphite and PTFE showing the lowest wear and coefficient of friction [7]. Rheological analysis revealed that greases with medium-viscosity synthetic base oils and urea thickeners maintain better oil film and lower friction, particularly under EV operating conditions [5]. Additionally, thermal oxidation common in machinery degrades oil quality; hence, methods like the rotating oxygen bomb (ROB), IR spectroscopy, and RULER analysis are combined to monitor antioxidant depletion accurately [8, 9, 11]. ROB evaluates oxygen resistance, IR tracks oxidation via absorbance changes, and RULER electrochemically quantifies remaining phenolic and amine antioxidants [9].

Used oils can also be converted into diesel-like fuels via pyrolysis and hydrocracking, with properties such as viscosity, density, sulfur content, and heating value comparable to standard diesel [1]. Studies on multigrade and monograde Pakistani engine oils show that viscosity index and flash point decrease over time, requiring timely replacement typically between 800 to 2200 km depending on oil type and vehicle weight to prevent engine wear [4]. Electric and hybrid vehicles demand lubricants with specialized electrical, thermal, and tribological properties to manage intermittent motor activity, high acceleration, and heat dissipation, making advanced lubricant formulations critical for performance and durability [6]. Lubricating oil is the composed of 80–90% petroleum-derived hydrocarbons and 10–20% additives, plays a key role in reducing friction, wear, and heat in machinery [10]. Toxicity concerns also remain, as degraded oils contain elevated levels of PAHs and can cause dermal or respiratory harm, highlighting the need for risk assessments and regulatory compliance [10].

1.2 Biolubricant

Biolubricants, derived from renewable sources like vegetable oils, waste cooking oils, and non-edible feedstocks, offer excellent biodegradability, low toxicity, and strong physicochemical and tribological properties compared to conventional mineral-based oils [12]. Vegetable oils such as castor, jatropha, jojoba, and palm are widely used but face limitations like poor oxidative and thermal stability, low pour points, and cold-flow behavior, which are addressed through chemical modifications like epoxidation, transesterification, esterification, and hydroxylation [13, 14, 16, 18, 29]. Rubber seed oil modified into epoxidized and hydroxylated forms showed improved thermal stability and a higher viscosity index of 380.65, making it comparable to castor oil but with better oxidative resistance due to lower iodine values [13]. Similarly, ricinoleic acid was chemically transformed into tetraesters via transesterification and esterification using polyols like TMP and pentaerythritol, resulting in enhanced viscosity index, lower pour point, and reduced wear and friction under ASTM D4172 (ASTM- American Society for Testing and Materials) testing due to polar ester groups forming stable films on metal surfaces [14].

Used cooking oils like treated recycled vegetable oil (TRVO) also proved viable, demonstrating favorable friction COF = 0.00143 (COF stands for coefficient of friction) and wear (16.219 μm) values during machining tests, along with good thermal performance at low lubricant flow [15]. Oleic acid-based lubricants blended with 0.5 wt.% antioxidants (e.g., TBHQ) and 1.2 wt.% EVA showed significant tribological improvements, with up to 22% COF reduction and better wear resistance, especially at high speeds (2400 rpm) [21]. TMP esters from palm oil tested in direct valve train assemblies, particularly with a-C:H-coated cam/tappet interfaces, showed low friction torque and minimal surface damage, supporting their use in engine lubrication [17]. Biolubricants from non-edible jatropha and jojoba oils synthesized via optimized transesterification and epoxidation yielded high conversion rates (up to 248 ml), with improved viscosity and COF values as low as 0.045 [18, 29]. Combining fatty acids with amine additives or using ionic liquids enhanced lubrication performance more effectively than using fatty acids alone [22]. Engine oils blended with B30 biodiesel demonstrated lower friction (<0.06 COF), despite increases in viscosity and acid number due to oxidation and biodiesel dilution, while antioxidants reduced molecular degradation but increased wear [23].

Endurance tests with B30 biodiesel showed decreased kinematic viscosity and increased wear metals and contaminants over time, stressing the need for oil quality monitoring [24]. Biolubricants synthesized from rapeseed and mixed corn–sunflower oils through optimized transesterification showed high oxidative resistance and viscosity indices, though improvements could be made by using complex alcohols or blending with higher-viscosity base oils [25]. Waste feedstocks such as lignocellulosic biomass, plastics, and refuse-derived fuels processed via pyrolysis or hydrothermal liquefaction (HTL) yield bio-oils requiring catalytic upgrading to improve viscosity and reduce oxygen content for lubricant use [12]. Palm oil-based esters like TMPE and PE, especially when blended with mineral oil (20–80 wt.%), showed reduced friction and wear, with PE achieving a pour point below −37 °C and excellent low-temperature performance [19]. Modified PMO with TBHQ and EVA increased oxidative induction time by 4.5x and reduced COF and wear compared to unmodified PMO, although still slightly inferior to mineral oil VG68 [26]. In other tests, palm-based PE2088 blended with up to 10 wt.% additives achieved COF of 0.071 and 0.34 mm wear scar diameter (WSD), 25–31% better than engine oils, confirming its potential for high-performance lubrication [27]. High-oleic vegetable oils, including sunflower and soybean oils, exhibited Newtonian flow, high thermal stability, and strong performance under boundary and hydrodynamic regimes, offering sustainable alternatives to petroleum-based lubricants in metal machining [32]. Overall, with ongoing advances in chemical modification, antioxidant integration, and feedstock optimization, biolubricants present a viable path toward sustainable, high-performance lubrication systems across automotive, industrial, and environmentally sensitive applications [20, 22, 28, 30, 31].

1.3 Nanolubricant

Nanolubricants, synthesized by dispersing engineered nanoparticles into base oils or greases, have revolutionized tribology by significantly enhancing friction reduction, wear resistance, and thermal conductivity under extreme operating conditions [33–35]. These additives ranging from metal oxides (e.g., ZnO, CuO, Al_2O_3, TiO_2, Pr_6O_{11}) [35, 40, 44, 45, 59], sulfides (e.g., MoS_2) [44, 50], and carbides (e.g., Mo_2C, SiC) [48, 55], to carbon-based materials (e.g., reduced carbon nanotubes, graphene oxide, graphite, fullerene, graphene-cellulose composites) [36, 43, 52, 54] enhance lubricant performance through mechanisms such as tribo film formation**,** nano ball-bearing effects**,** mending and polishing actions, and surface repair [51, 58]. Hybrid systems (e.g., MgO/SiC, rGO-CuO) and over based nano detergents offer synergistic properties, enabling customized solutions for high-load, high-temperature applications in automotive, aerospace, and EV systems [33, 48, 41].

Surface modification techniques (e.g., surfactants like oleic acid, PIBSA) and dispersion strategies (e.g., ultrasonication, stearic acid capping) ensure long-term stability and compatibility with base oils [39, 55, 59]. Tribological tests (pin-on-disc tribotester, four-ball tester, ball-on-disk tribotester) confirm notable improvements in COF, WSD and flash point temperature parameter (FTP), with optimal concentrations (typically 0.1–0.5 wt.%) varying by nanoparticle type and application [35, 40, 44, 46, 57]. For instance, 0.3 wt.% Pr_6O_{11} and Mo_2C enhanced viscosity, reduced friction, and improved thermal properties [40, 55], while 0.5 wt.% RGO in Shell 5W-30 halved COF and wear [43]. Water-based lubricants enhanced with MgO/SiC and treated graphene oxide (tGO) demonstrate excellent thermal control and hydrodynamic lubrication in journal bearings [49]. In electric vehicles (EVs), nanolubricants such as BNNS/PEN composites and rGO show promise due to their ability to maintain low electro-viscosity, high thermal conductivity, and resistance to electro-corrosion under DC electrical fields [41].

Advanced studies incorporating molecular dynamics simulations and surface characterization tools (e.g., SEM, FTIR, UV-Vis, XRD, TGA) continue to elucidate the interfacial interactions and optimize nanoparticle selection, morphology, and loading [36, 43, 55, 59]. Recent studies [60–65] have further emphasized the development of green nanolubricants, utilizing nanoparticles synthesized via plant-mediated routes (e.g., *Azadirachta indica, Camellia sinensis*), which exhibit superior oxidation resistance and tribological behavior in vegetable oil esters [60, 62]. Emerging hybrid nanostructures such as rGO-$CuZnFe_2O_4$, MoS_2@Fe_3O_4, and TiO_2-SiO_2 improve tribological performance via combined rolling-sliding, catalytic, and magnetic mechanisms, offering COF reductions up to 60% in boundary lubrication [61, 64]. In extreme environments like marine gearboxes, wind turbines, and aerospace systems, nanolubricants doped with La_2O_3, ZrO_2, or WS_2 maintain thermo-viscosity, reduce scuffing, and allow longer drain intervals [63]. The inclusion of surface-modified nanoparticles in PAO and ester basestocks has yielded excellent thermo-oxidative stability (>250 °C) and deposit control with low sludge formation [60, 65]. In parallel, optimization algorithms such as RSM, ANN, and ANFIS are being used to refine nanoparticle morphology, loading, and surfactant ratios for maximal tribological benefit [62, 65]. These trends are propelling nanolubricants into next-generation smart lubrication systems, including low-dielectric and electro-compatible formulations tailored for electric drivetrains**,** MEMS, and robotic**s**, marking their emergence as critical components for sustainable, energy-efficient, and intelligent lubrication technologies [60–65].

Traditional lubricants based on oils and greases pose significant environmental risks due to their petroleum origins and toxic additives. To address these concerns, researchers have developed a novel, eco-friendly lubricant: a water-based colloidal gel composed of silica nanoparticles and common salt. This gel exhibits thixotropic behavior, meaning it can regain its structure after shear forces are removed. In tribological tests involving steel-steel interfaces, the gel demonstrated remarkable performance, reducing friction by up to 97% compared to dry conditions and 97.04% compared to water lubrication. Additionally, the specific wear rate decreased by over 96% under both dry and water-lubricated conditions. These improvements are attributed to the gel's self-repairing properties, continuous tribo-film formation, and the nano-bearing effect of silica nanoparticles. This innovative lubricant offers a promising, sustainable alternative to traditional lubricants, combining low environmental impact with enhanced performance [200].

1.4 Microalgae Based Lubricant

Microalgae-derived lubricants represent a sustainable and eco-friendly alternative to conventional petroleum-based oils, offering biodegradable, low-toxicity formulations with reduced greenhouse gas emissions [66]. Efficient production relies on microalgae selection, cultivation, and harvesting techniques, while downstream processes like green solvent extraction and solvent-reduction strategies must be prioritized to limit ecological damage [66]. Despite good tribological performance, microalgal lubricants struggle with thermal and oxidative stability at high temperatures, which limits their application in internal combustion engines, prompting research into nanoparticle additives to enhance performance [66]. Spirulina platensis is a blue-green microalga belonging to the cyanobacteria group that grows naturally in freshwater and alkaline lakes. *Spirulina platensis* is a type of microalgae known for its high protein, lipid, and nutrient content. It grows naturally in freshwater and alkaline environments and is widely used for producing biofuels and biolubricants. Its oil can be converted into eco-friendly lubricants with good stability and performance, making it a sustainable alternative to petroleum-based oils [66].

Microalgae such as *Chlorella vulgaris* can also be cultivated in emulsified crude oil for dual benefits biomass production and bioremediation with growth rates increasing from 0.477 to 0.784 day^{-1} as oil concentration rises, and modified Monod kinetics using interfacial area providing accurate modeling of degradation behavior [67]. These organisms are also suitable for producing metalworking fluids (MWFs) in minimum quantity lubrication (MQL) operations, thanks to their rich fatty acid profiles and natural biodegradability; however, scalability is constrained by photobioreactor limitations and high resource demands, which are being addressed by exploring agro-industrial wastewater as a growth medium and developing supercritical fluid extraction methods [68]. In hydrogen-powered engines, modified microalgae oil (MMO) blended at 10% (MMO-10) has reduced the coefficient of friction by 10.1% and enhanced heat dissipation, although acid value remains a concern requiring improved esterification and replacement of toxic extreme pressure additives with greener alternatives [69].

Species like *Chlorella vulgaris* are highly attractive due to their rapid growth and high fat content, which can be catalytically converted into green diesel, jet fuel, and lubricants using zeolite catalysts such as HZSM-5, whose activity and selectivity improve upon doping with rare-earth metals, allowing operation at relatively lower temperatures (550–650 °C) [70]. Enzymatic transesterification of oils from *Aurantiochytrium sp.* using lipases at room temperature achieved 55% wt. biodiesel yield with reduced degradation of unsaturated fatty acids, outperforming oil from *C. vulgaris*, which yielded only 25% due to its low 1% wt. lipid content [71]. In contrast, *Chaetoceros sp.* has demonstrated 70% oil yield with promising lubrication-related properties, such as 6.2 mm^2/s viscosity, 2.5339 mg/g acid value, and a favorable fatty acid profile (e.g., 20.1% 1-nonadecenoic acid), which supports high thermal performance and wear resistance [72]. Compared to vegetable oils (VOs), microalgae can be cultivated on non-arable land with minimal water input and tailored fatty acid compositions by adjusting cultivation parameters, making them a non-competitive, highly flexible feedstock for lubricants [73]. Their lipid profiles, dominated by long-chain unsaturated fatty acids such as Docosahexaenoic Acid (DHA) and Eicosapentaenoic Acid (EPA), confer superior oxidative stability and low-temperature flow characteristics, crucial for advanced lubrication systems and green technologies [74].

However, the toxicity of traditional extraction methods like chloroform/methanol (2:1) limits their scalability, so food-grade solvents such as hexane: isopropanol (3:2) are preferred, achieving up to 13.93% yield while preserving favorable lipid profiles rich in palmitic, oleic, and stearic acids, essential for high-performance lubricants [75]. Microalgae offer a much higher lipid productivity than soybeans and can complete growth cycles in just 15 days; however, the economic feasibility of oil production hinges on heterotrophic cultivation strategies, cell concentration improvements, and energy-efficient solvent recovery techniques such as pervaporation membranes, which could improve yield beyond the current 3.9 wt% oil in methanol-rich solvent systems [76]. Optimized Soxhlet extraction using heptane with *C. vulgaris* yielded 61.27% oil at 65 °C and 600 rpm over 5 hours, demonstrating the importance of temperature, mixing rate, and solvent choice in maximizing oil recovery without decomposing cell material [77]. Thermochemical methods like hydrothermal liquefaction (HTL) and pyrolysis also offer high oil yields (up to 60%) and energy density (46 MJ/kg), with catalysts improving fuel quality and expanding applications to sustainable lubricants and fuels [78].

Microalgal oil from strains collected from CO_2-enriched environments, such as those in Nike Lake, has shown promising characteristics (density 0.892 g/cm^3, saponification value 200 mg KOH/g, iodine value 100–120), indicating its readiness for conversion into ester-based biolubricants [79]. Even defatted biomass residues from oil extraction retain value for aquafeed or lubricant precursor synthesis; for example, DHA-rich *Schizochytrium sp.* and *Nannochloropsis oculata* improve fish growth and nutritional quality while reducing production costs and reliance on marine ingredients, aligning with circular bioeconomy goals [80]. Blending microalgal oil with waste cooking oil (WCO) yielded high-quality biodiesel with a cetane number of 77.76, viscosity of 4.50 mm^2/s, and acid value of just 0.049 mg KOH/g. The optimized transesterification process—conducted at 60 °C, 2% catalyst loading, and 12:1 methanol-to-oil ratio—achieved 98.82% conversion, confirming microalgae's dual potential in biodiesel and biolubricant applications [81]. The oil from *Nannochloropsis salina*, rich in palmitic and palmitoleic acids, is converted into azelaic acid and heptanoic acid via ozonolysis with yields of 84%, enabling the synthesis of polyester diols for PU-based lubricants and green solvents like renewable hexane, maximizing oil utilization and value [82]. In aquaculture, microalgae oils such as Veramaris® performed comparably to fish oil in gilthead seabream diets, with >99% survival and similar EPA+DHA content in fillets, while offering lower dioxin and PCB contamination, indicating the suitability of such oils as safe, high-purity lubricant precursors [83].

Efficient oil extraction from *Chlorophyta sp.* using n-hexane/ether (4:1) at 61.31 °C for 2.54 hours yielded 18.29 wt.%, and GC-MS and FTIR analyses confirmed the presence of alkanes, esters, and unsaturated fatty acids like oleic acid, with low free fatty acid levels (0.62 wt.%) suitable for one-step biodiesel or lubricant conversion [84]. With rapid developments in algal strain engineering, cultivation systems, and omics tools, lipid accumulation in stress-resistant microalgae has increased, allowing controlled oil production in photobioreactors. Gene-edited strains grown under optimized lighting and nutrient regimes show potential for consistent, scalable oil output for eco-friendly lubricants [85]. High-lipid strains such as *Nannochloropsis sp., Tetraselmis sp.*, *Chlorella sp.*, and *Dunaliella salina* are used for their favorable fatty acid profiles, especially under nutrient-stress conditions, which promote accumulation of C16:0, C18:1, and C18:2—key components for stable lubricants. *Chlorella sp. BR2* demonstrated 81.4% of ideal FAs for lubricants, while *Nannochloropsis sp. BR2* yielded 73.6% [86].

Additionally, microalgae play an essential role in biodegradation of spent oil waste (SOW), using hydrocarbons as carbon sources and degrading toxic components via enzymatic redox pathways, supporting their dual function as pollutant remediators and lubricant feedstock producers. From 2005 to 2023, microalgae-focused SOW research increased by over 80%, highlighting growing interest in these sustainable solutions [87]. Lastly, microalgae-derived oils rich in ω-3 PUFAs like DHA and EPA require careful extraction due to oxidative sensitivity, but stabilization via antioxidants, encapsulation, or nano emulsions can significantly extend their shelf life, making them viable for advanced lubrication systems with minimal toxicity [88]. Together, these interconnected advances position microalgae as a high-potential source for developing eco-friendly, high-performance lubricants across industrial, automotive, and renewable energy sectors. Botryococcus braunii is a green colonial microalga known for producing significant amounts of renewable hydrocarbons through photosynthesis. However, its slow growth rate presents challenges in large-scale cultivation. To address this, researchers have explored various cultivation methods to enhance biomass and hydrocarbon production. One promising approach is attached growth cultivation, where algae grow on surfaces, forming biofilms. This method has shown potential in improving productivity and reducing costs. Additionally, the milking technique, which involves periodically harvesting hydrocarbons without harvesting the entire biomass, has been proposed to efficiently extract hydrocarbons. These combined strategies offer a sustainable and cost-effective pathway for producing algae oil from B. braunii [202].

1.5 Bionanolubricant

Bionanolubricants formulated from renewable oils such as castor, soybean, jatropha, palm, rice bran, sesame, jojoba, hazelnut, sunflower, and mahua are gaining momentum as high-performance, biodegradable, and eco-safe alternatives to petroleum-based lubricants, especially when reinforced with nanoparticles that significantly boost tribological and thermal behavior [89-106]. Functionalized calcium carbonate (f-$CaCO_3$) nanoparticles added at 0.15 wt% to castor and soybean oils reduced friction coefficients by 14% and 18%, respectively, while wear width dropped by 27% and 24% under sliding conditions, aided by rolling effects and tribofilm formation validated via SEM and Raman microscopy [89]. Environmentally acceptable ionanofluids (INLs) using TiO_2 nanoparticles and ionic liquids like (EMIM, DCN) and (P66614, BTMPP) in rice bran and sesame oils revealed stable formulations over 30 days when specific surfactant-to-additive ratios (1:2 to 1:6) were maintained, demonstrating their potential for long-term dispersion and eco-friendly lubrication [90].

Incorporating graphene nanoplatelets (GNP), copper (Cu), and TiO_2 into soybean oil led to significant tribological enhancements, with GNP reducing friction by 30% and wear by 40%, showing optimal performance at 1.0 wt% for GNP and 0.5–1.0 wt% for TiO_2, while maintaining stability up to 100 °C and efficiency across all lubrication regimes [91]. Jatropha oil infused with in situ synthesized TiO_2 nanoparticles (0.1% to 0.5% v/v) showed a 32–38% reduction in frictional force and a 43.81% increase in seizure pressure, alongside a 15% rise in fire point, with improved corrosion resistance and biodegradability (BOD/COD > 0.5), while cutting synthesis costs by 37% [92]. Chemically modified jatropha and jojoba oils (via epoxidation and transesterification using H_2SO_4 and HCl) enhanced oxidative stability, with iodine values dropping to 5 and 6, and when combined with Microwalled carbon nanotubes (MWCNTs) and TiO_2 using Triton X-100, achieved wear reductions of 94.68% (TiO_2) and 79.85% (MWCNT), with minimal COF values (0.059 and 0.061), though high humidity posed corrosion and hydrolytic stability issues [93].

Silver nanoparticles (AgNPs) at 0.75 wt% in Jatropha oil achieved a 27% COF reduction and 54% wear rate reduction compared to base oil, showing strong bonding at worn interfaces as evidenced by FESEM and XRD, alongside improved viscosity and thermal conductivity, especially outperforming Pongamia oil formulations [94]. Bio-based trimethylolpropane ester (TMPe) with graphene oxide (GO) nanoparticles at 0.05–0.5 wt% reduced COF by 21% and wear scar diameter by 6.3%, with optimal anti-wear behavior at 0.1 wt%, though excessive GO led to agglomeration and increased surface abrasion [95]. Modified Calophyllum inophyllum oil (MCIO) with 0.025 wt% nano-activated carbon (NAC), produced via sonication, achieved a COF of 0.0551 and a wear rate of 5.91×10^{-7} $mm^3/N \cdot m$, outperforming neat MCIO and synthetic esters, as the porous NAC structure helped form stable protective tribofilms [96].

In the context of electric vehicles, palm oil-based bionanolubricants enriched with graphene, TiO_2, Al_2O_3, and ZnO showed friction reductions of 26.21%–34% and wear reductions up to 30%, delivering superior heat dissipation and efficiency essential for EV drivetrain and bearings under high-temperature conditions [97]. Blending 10% raw mahua oil with 90% 10W30 lubricant (B10) and dispersing GNPs (0.25–0.75 mg/L) revealed 13.10% lower COF and 80% reduced wear loss at 0.25% GNP, while under dry conditions the same sample showed 94.1% lower wear loss and 63.6% lower friction force, due to tribo-film formation and rolling mechanism, though higher concentrations led to agglomeration [98]. Similarly, blending 10% mahua oil with 20W40 oil and enhancing with MWCNTs showed the best performance at 0.25 wt%, reducing COF by 43.10%, wear rate by 70.36%, and frictional force by 46%, with SEM revealing fewer pit marks and smoother surfaces due to mending and rolling mechanisms, although agglomeration occurred at higher MWCNT levels beyond 0.5 wt% [100]. Grease formulations using palm olein and MoS_2 (nano vs. micro-sized) at 0.5 wt% showed nano-MoS_2 performing better in reducing COF and surface roughness, with weld points of 180 kg in both, and tribo-film formation confirmed via EDS and SEM, making them suitable for extreme pressure applications [99].

Hazelnut oil with ZnO (0.5%) and sunflower oil with MoS_2 (1%) achieved COF reductions of 12.6% and 35.8%, respectively, and improved viscosity by up to 16.6% at 80 °C, with load-carrying capacities of 1000 N and 1800 N, though agglomeration and biodegradability concerns with inorganic additives persist [101]. Enhancing jatropha oil with PDMS and hexagonal boron nitride (h-BN) showed synergistic tribological improvements COF reduced by 35.23%, wear scar by 29.2%, and surface roughness by 63.78% thanks to h-BN's rolling and mending action and PDMS's film-forming and shearing ability, though PDMS had limited corrosion protection under prolonged exposure [102]. Further enhancement of modified jatropha oil (MJO) with 0.025 wt% activated carbon (AC) and hybrid nanoparticles like hBN, TiO_2, and WS_2 formed advanced nanofluids MJOah, MJOat, and MJOaw where MJOah had the lowest COF (0.05465), smallest wear scar diameter (595.3 µm), and minimal wear rate (2.964×10^{-7} mm^3/s), supported by smoother wear tracks in SEM images [103].

In railway lubrication, palm ester-based bio-greases thickened with calcium complex soap and reinforced with 5 wt% $CaCO_3$ and 3 wt% hBN achieved a 24% COF reduction and 17% less pin wear compared to commercial rail greases, confirming their potential in environmentally sensitive, high-stress applications [104]. Nanoparticles also serve as effective slip agents in polymer-based lubricant systems, with polypropylene (PP) composites incorporating nanoscale talc, stearamide, and beeswax revealing that stearamide yielded the lowest COF and talc the highest viscosity reduction, while DSC and FTIR confirmed strong additive–polymer interactions without altering melting temperatures [105]. Lastly, nano-lubricants using sunflower and palm oils with 0.2 wt% TiO_2 and CuO dispersed via ultrasonication showed remarkable COF reductions of 51% (TiO_2) and 48% (CuO), along with high load-wear index (LWI) values, smoother wear surfaces confirmed by SEM, and strong tribofilm and tribosintering effects, making them suitable for gear lubrication under high load [106].

These detailed advancements collectively demonstrate that bionanolubricants, especially those based on non-edible oils enhanced with nano-additives, offer technically viable, thermally stable, and environmentally friendly solutions for next-generation lubrication across automotive, industrial, EV, and gear applications [89-106]. Researchers have developed a novel blend of Karanja and Neem oils, enhanced with hexagonal boron nitride (hBN) nanoparticles, to create a more efficient and environmentally friendly lubricant. These oils are biodegradable, and less toxic compared to traditional petroleum-based lubricants. By incorporating hBN nanoparticles, the blend's performance was significantly improved. Tests revealed that the addition of hBN reduced friction and wear, leading to better lubrication efficiency. The study also examined the blend's chemical and physical properties to understand how the nanoparticles interact with the oils. This approach offers a sustainable alternative to conventional lubricants, combining natural oils with advanced nanotechnology for enhanced performance [201].

1.6 Pin on Disc Tribometer

A pin-on-disc tribometer, widely utilized in tribological evaluations, plays a pivotal role in analyzing friction, lubrication, and wear behaviors across various material combinations and lubricant formulations, especially under diverse operational conditions. A specialized micro-scale pin-on-disc setup equipped with laser-based displacement sensors enabled precise force and film thickness measurements, showing that at low sliding speeds, contact between surfaces is predominant, while at higher speeds, a stable lubricant film develops, transitioning into a hydrodynamic regime where friction increases gradually with speed due to viscous drag forces, confirming high repeatability and reliability for sub-mm scale lubricant assessments [107]. Building on this, sunflower oil-based lubricants enhanced with biodiesel (B20, B40) and ZnO nanoparticles (0.2%, 0.5%) demonstrated excellent tribological responses under dry and lubricated conditions, tested on stainless steel discs and brass pins across loads of 1–5 kgf and speeds of 300–700 rpm. The tribological behavior of a PIN was evaluated under vegetable oil-based lubricants enhanced with biodiesel and metal oxide nanoparticles.

Different lubricant mixtures were tested, specifically Lubricant Formulation 5 (LC5), Lubricant Formulation 7 (LC7), and Lubricant Formulation 8 (LC8), to investigate how variations in composition affected friction, wear, and overall performance. Friction and wear were highest under dry conditions, reduced with base oil, and were lowest with ZnO nano-enhancements, particularly LC5 at low load/low speed, LC8 at high load/low speed, and LC7 at high load/high speed, indicating strong nanoparticle influence on surface protection, while the COF was more dependent on surface interactions than load or speed [108]. Palm oil biodiesel-diesel blends (10–50%) evaluated under 30–90 N loads at 150 rpm using a ball-on-disc tribometer revealed that higher biodiesel concentrations offered superior anti-wear properties, with B40 and B50 resulting in the lowest wear (8 mg), attributed to their high viscosity which enabled thicker lubricating films. Friction increased with load for all except B10, possibly due to oxidative degradation or film instability, while B30 balanced both friction and wear reduction effectively [109].

Further insight came from using pentaerythritol ester (PE) biolubricants infused with CuO nanoparticles (0.1–0.5 wt.%) tested in a four-ball tribometer per ASTM D4172; the 0.3 wt.% CuO formulation showed the lowest COF, torque, and WSD, thanks to its smoother worn surfaces confirmed by SEM. Ultrasonic irradiation enhanced nanoparticle dispersion, improving lubricant quality, and ensuring ASTM compliance in terms of viscosity, flash point, pour point, and acid number, with CuO aiding in tribofilm formation and wear resistance [110]. Magnetically responsive ferrofluid lubricants significantly outperformed conventional oils in friction and wear reduction—up to 60% and 74% respectively—when tested on block-on-ring tribometers following a G77 setup. Ferritic shafts showed better outcomes than austenitic ones, and optimal magnetic field strength (350 Gauss) minimized friction and wear compared to higher fields (650 Gauss), emphasizing the importance of stability and environmental control, with stable ferrofluids offering greater efficiency than unstable magnetic nanofluids [111].

A cost-effective pin-on-disc tribometer adhering to ASTM G99–17 was developed to test nano fly ash (0.5 wt.%, <100 nm) dispersed in SAE 10W–30 oil on AISI 4140 steel under a load of 15 N, speed of 1.5 m/s, and distance of 1500 m. Compared to dry and base oil runs, the nano fly ash lubricant reduced COF by 76.5% and wear by 28.9%, attributed to the formation of durable tribofilms and a hybrid rolling-sliding mechanism, with smoother worn surfaces verified through SEM, highlighting its economic and technical viability [112]. Blends of castor oil with commercial 20W40 engine oil in 10% and 20% volume ratios tested at 50 N and 100 N load under 80 rpm for one hour demonstrated that even at lower concentrations, castor oil enhanced lubrication under light loads, with both blends showing stable tribological behavior. Although wear and friction were slightly higher than pure engine oil, the results remained within acceptable limits, making castor oil a viable renewable additive with environmental advantages [113].

In another targeted study of engine-relevant tribological behavior, grey cast iron discs were slid against real piston ring segments using a pin-on-disc tribometer under constant (140 N) and incremental (20–140 N) loading for 105 minutes, with commercial lubricants SAE10W30, SAE20W40, and SAE20W50. SAE20W50 displayed the best friction and wear characteristics due to its viscosity and antioxidant content, yet SAE20W40 was recommended for modern engines due to better flow characteristics at low temperatures, avoiding sludge buildup and cold-start issues despite slightly lesser tribological performance [114]. In industrial applications, blending palm oil and virgin coconut oil (VCO) into 85W140 GL5 gear oil showed notable tribological improvements. Using a pin-on-disc rig per ASTM G99 at 600–900 rpm and 30–60 N loads, the 15% VCO blend achieved the lowest COF (at 750 rpm, 45 N), while the 30% palm oil blend yielded the lowest wear rate (0.0000019 mm^3/Nm) at 600 rpm, 45 N. Surface roughness was significantly reduced (Ra = 0.04 μm), and viscosity testing confirmed the base oil retained the highest viscosity, while 30% VCO had the lowest. Palm oil enhanced wear resistance, and VCO reduced friction, offering a strong case for dual bio-oil blending in sustainable lubrication [115].

Lastly, palm kernel oil (PKO) lubricants augmented with CuO nanoparticles showed drastic improvements when tested under 9.8 N load at 0.2 m/s for 60 minutes using a pin-on-disc tribotester, reducing COF by 56% and WSD by 48% compared to SAE40 mineral oil. SEM and EDX revealed that CuO acted as a rolling medium, limiting metal contact and lowering roughness by 43.7%, thus establishing PKO-CuO as an efficient alternative to petroleum-based lubricants [116]. These wide-ranging evaluations using pin-on-disc and related tribometers, from microscale precision systems [107] to industry-grade mechanical configurations [108–116], demonstrate the robustness and adaptability of such instruments in assessing the tribological performance of bio-based, nano-enhanced, and hybrid lubricants. From the effectiveness of metal oxide nanoparticles (ZnO, CuO) in enhancing wear resistance [108,110,116], to the role of viscosity and nanoparticle stability in forming protective tribofilms [109,111,115], and the validation of sustainable oil blends for both automotive and industrial applications [113–115], the pin-on-disc tribometer continues to provide critical insights into material-lubricant interactions essential for next-generation lubrication solutions.

1.7 MULTIMOORA

The MULTIMOORA (Multi-Objective Optimization by Ratio Analysis plus Full Multiplicative Form) method is a technically rigorous and universally adaptable multi-criteria decision-making (MCDM) framework that integrates three functionally distinct optimization components—the Ratio System (RS), the Reference Point Approach (RPA), and the Full Multiplicative Form (FMF) to analyze complex decision-making scenarios involving conflicting objectives without compromising objectivity or dimensional integrity [117]. In the RS, performance values are normalized using the square root of the sum of squares to generate unitless ratios, allowing fair comparison across diverse metrics, with beneficial criteria aggregated and non-beneficial ones subtracted [117, 119]. The RPA, grounded in the Tchebycheff min-max metric, refines decision robustness by evaluating deviations from ideal values, avoiding the bias found in traditional compromise-based methods like TOPSIS [117, 120], while the FMF computes the geometric product of normalized scores, reinforcing internal consistency and ordinal validity [121, 122].

Importantly, MULTIMOORA avoids arbitrary data transformations, preserving original data structures for ethical and social accountability, particularly useful in post-socialist or stakeholder-rich environments [122, 123]. It satisfies seven robustness conditions, including handling non-correlated objectives, supporting stakeholder inclusivity, and allowing both ordinal and cardinal analysis using up-to-date information and cross-verifying ranking techniques [120, 123]. The methodology has demonstrated practical effectiveness in contexts like contractor ranking in Lithuania [118, 120], road design planning in Germany [119], and architectural optimization for heating efficiency using wall-to-window ratios [121], with insights revealing the hidden impact of organizational experience over pricing models [118]. In energy-efficient design and economic development initiatives, MULTIMOORA facilitated unbiased evaluations based on normalized criteria [123]. Its objectivity stems from mathematical normalization rather than subjective weight allocation, enhancing its credibility in preference-sensitive applications [120, 117]. The fuzzy-enhanced MULTIMOORA-FG incorporates triangular fuzzy numbers in all three components, enabling human-resource-focused applications such as expert-driven personnel selection under linguistic ambiguity [125].

To consolidate the outputs of RS, RPA, and FMF, dominance theory is employed to derive a unified, consistent ranking [126, 130], which has been validated in engineering and manufacturing contexts. For example, fuzzy entropy and Shannon entropy-based criteria weights were effectively applied in selecting materials for biomedical and automotive parts, balancing subjective expert evaluations with objective statistical measures [127, 128, 129]. These entropy-enhanced versions showed high Spearman rank correlation coefficients (0.96, 0.93), confirming strong agreement with other MCDM methods [129]. Interval and fuzzy MULTIMOORA adaptations—featuring entropy weighting and interval arithmetic—successfully handled ambiguous data during critical applications like material ranking for turbine blades, ensuring risk-adjusted performance evaluation based on durability and mechanical thresholds [130, 134]. Unlike SAW and TOPSIS, MULTIMOORA transparently preserves beneficial and non-beneficial criteria distinctions without distortion [131]. The method's hybrid versions, enhanced with advanced fuzzy theories such as circular q-rung orthopair fuzzy sets (Cq-ROFS), Picture Fuzzy Sets (PFS), and probabilistic linguistic term sets (PLTS), supported strategic assessments in diverse contexts like mental health strategy, education quality, and organizational appraisal [132, 133, 135], often utilizing aggregation operators like the Circular q-Rung Orthopair Fuzzy Weighted Muirhead Mean (Cq ROFWMM) for accurate inter-criteria modeling [132].

In group decision-making with high uncertainty, PL-MULTIMOORA merged subjective inputs with correlation-based objective weights and refined rankings via the Borda rule [135], reinforcing decision resilience. Comparative studies affirmed consistency with methods like AHP-TOPSIS, fuzzy VIKOR, and WPM [129, 128]. Further advancements integrated MULTIMOORA with fuzzy extensions in ICT strategy, healthcare prioritization, urban sustainability, transport engineering, and internal combustion engine optimization—where biodiesel blends like B94NM5C1 were optimally selected using neutrosophic MULTIMOORA combined with SWARA [140]. Bipolar fuzzy MULTIMOORA handled dual-polarity expert opinions in socio-technical policy settings [138], while intuitionistic multiplicative MULTIMOORA (IM-MULTIMOORA) introduced new distance metrics (e.g., Jaccard and Dice) and Grey Relational Analysis-based weights for enhanced hospital equipment decisions [139]. Its robustness in crisp and uncertain environments has enabled implementation in Excel and programming environments, with bibliometric studies highlighting its growing influence in sustainability, engineering, and governance, while identifying gaps in reference point refinement and group dynamics modeling [137]. Hybrid variants such as group interval MULTIMOORA, integrating two-tier Best–Worst Method (BWM) and interval entropy weights, successfully evaluated hybrid engine components under experimental uncertainty [140], while interval type-2 fuzzy MULTIMOORA improved FMEA precision in steel manufacturing by pinpointing critical failure modes [141].

In the healthcare sector, single-valued trapezoidal neutrosophic numbers (SVTNN) were used to assess surgical risks, where unclear diagnosis emerged as the highest-risk failure mode [143]. Similarly, TrNN-based MULTIMOORA outperformed classical dominance-based tools in banking decisions under incomplete data by applying correlation and standard deviation-derived weights [144]. The MULTIMOOSRAL model extended MULTIMOORA with additional tools like Logarithmic Approximation, Aggregated Function, and MOOSRA-WASPAS integration, yielding accurate supplier rankings in close-performance scenarios [145]. MULTIMOORA outperformed TOPSIS and WASPAS in Turkish university site selection by demonstrating weight insensitivity and strong sensitivity analysis robustness [146] and was applied in warehouse candidate selection using SVNS and CRITIC-derived weights across eight attributes [147]. Subway project planning benefited from an IMVN-PT-MULTIMOORA hybrid integrating prospect theory and generalized MVN weighted operators to accommodate behavioral irrationality in complex construction settings [148].

Fuzzy AHP and fuzzy MULTIMOORA effectively modeled uncertainties in supplier decisions by using dominance theory for stable, multi-criteria-based rankings [149]. In CCUS site evaluations, D numbers and entropy weighting enabled accurate assessment of multifactorial risks under fuzzy MULTIMOORA [150]. Boiler selection under expert hesitancy leveraged TraFNNs, OPA, and CCSD-based rankings for improved group decision accuracy [151], while HF-MULTIMOORA combined fuzzy AHP with envelope evaluation to compare 13 criteria in gas boiler selection [152]. In disaster risk reduction education, Dempster–Shafer Theory transformed linguistic ratings into probabilistic distributions for robust policy selection using an 18-criteria MULTIMOORA framework [153]. Ship engine room fire risk assessment combined nonlinear programming, intuitionistic fuzzy modeling, and expert weight elicitation to outperform standard MCDM techniques in precision [154]. MULTIMOORA also aided mining method selection using 2-tuple spherical fuzzy linguistic sets and 2TLSFWA operators, selecting optimal phosphate extraction methods [155].

In new product development, Pythagorean fuzzy sets and PFWA-based (PFWA- Pythagorean Fuzzy Weighted Averaging) MULTIMOORA yielded consistent gaming software rankings under vague evaluations [156]. Communication circuit evaluations used BPNS-enhanced MULTIMOORA to model bipolar expert opinions, capturing nuanced preferences better than MOORA variants [157]. Geologic CO_2 site selection utilized Schweizer–Sklar-based aggregation and PFSSPA operators to align stakeholder risk preferences and decision robustness [158]. In pandemic triage, entropy-weighted MULTIMOORA ranked patients based on AI-evaluated symptoms and pneumonia risks, streamlining real-time health prioritization [159]. INS and regret theory-based INN-RT-MULTIMOORA was applied to school evaluation, incorporating regret-driven preference modeling and Borda rule refinement [160]. The welding process selection used fuzzy BWM and half-quadratic optimization within MULTIMOORA to model trust indices and eliminate circular dominance issues [161].

In manufacturing, QFD-MULTIMOORA, combined with fuzzy BWM, DEMATEL, TRIZ, and Kano models, reduced design complexity while integrating customer voice in sustainable product planning [162]. In tribology, brake pad material selection using red mud bronze composites applied AHP-MULTIMOORA, with coefficients of friction, wear rate, and hardness receiving weights of 0.423, 0.205, and 0.088 respectively, aligning with MOOSRA outputs [163]. For logistics provider evaluation, BWM-WASPAS-MULTIMOORA under q-ROF modeling handled unknown weights via q-ROFFIWA and q-ROFFIWG operators, modeling inter-criteria influence [164]. Outsourcing under manufacturing uncertainty applied probabilistic hesitant fuzzy sets and Aczel–Alsina aggregation with entropy weighting to mitigate expert bias in final decisions [165]. Spherical fuzzy BWM with MULTIMOORA was used to identify ideal electric bus charging stations, with “Topkapi” scoring highest based on a 4-tier, 22-subcriteria model [166]. MG PF PRSs and MULTIMOORA together enabled multi-source decision integration in healthcare and smart city planning via Dempster’s rule [167], while spreadsheet-compatible models combining MULTIMOORA and PIPRECIA-S improved personnel selection efficiency [168].

Statistical analysis shows 76.28% of MOORA variants are hybrid, with MULTIMOORA adapting methods like MEREC, IDOCRIW, and KEMIRA for improved mechanical design optimization [169].

The Rank Position Method paired with MULTIMOORA revealed operational–sustainability imbalances in Turkish ports, where Mersin led operationally but Socar ranked highest overall [170]. In Vietnam's petroleum industry, IVF-MULTIMOOSRAL ranked ten suppliers under 15 sub-criteria with robust sensitivity results [171]. MULTIMOORA also guided agricultural decisions via FHSs, SPOTIS, and RF, identifying maize ($A_7 = 0.526$) as most suitable for crop diversification [172], and rated SME credit worthiness using interval type-2 fuzzy QFD-MULTIMOORA with extended Borda rule for precise evaluations [173]. DFS-AHP and DFS-MULTIMOORA ranked infectious disease risks across Istanbul, identifying Bağcılar as highest risk due to poor sanitation [174]. In green supply chains, QSBN-based Bayesian MULTIMOORA used PLNs and Deng entropy to capture belief interference under uncertainty [175], while site selection for PV waste centers was guided by rough Z-numbers and expert judgment reliability [176]. Psychologically driven technology investment decisions used PULTS, regret theory, and hybrid CRITIC-BWM for accurate high-tech evaluations [177]. For tracking Indonesia's SDG progress, MULTIMOORA revealed national leadership in 2022 but regional disparities and cost challenges [178]. Renewable energy rankings in Isfahan identified solar PV as most viable using fuzzy Dematel-based ANP and MULTIMOORA, where economic criteria had the highest weight (0.2505) [179]. PFS-based MM-MULTIMOORA improved physical education quality assessments by accurately modeling neutrality, membership, and non-membership [180].

A DNMEREC-integrated IVIFS-MULTIMOORA model supported green tech investments, applying Kendall's W and chi-square for consistency checks before applying the Borda rule or optimization [181]. OECD health system evaluation integrated UHC indices, GDP expenditures, and mortality rates into a balanced and collinearity-free MULTIMOORA ranking [182], while Ashanti's gold mining sites were fairly assessed with MULTIMOORA, ranking site S3 highest [183]. Deep HVAC retrofit evaluation in Italy balanced comfort with emissions reductions (39–43%), validating scenario A via stakeholder-aware criteria [184]. Agricultural policy decisions leveraged intuitionistic fuzzy graphs and MULTIMOORA to ensure equity and accuracy in welfare planning [185]. UAV selection involved fuzzy nonlinear decomposition and PSO-SSM optimization for subjective weights, with CRITIC for objective evaluation, ranking Agribot MX highest [186]. Noncommunicable disease prevalence across Europe was assessed with CRITIC-weighted MULTIMOORA, correlating rankings with income levels—Switzerland and Iceland ranking lowest in NCDs [187]. Rail freight logistics used single-valued q-ROFS and CRITIC-weighted MULTIMOORA to identify infrastructure investment as the most effective strategy [188], and European electricity generation rankings favored biomass CHP (straw and wood), though safety remained a concern [189]. ESG risk on the Warsaw Stock Exchange was evaluated using EU-aligned disclosure indicators, balancing financial and environmental responsibility [190]. Wastewater system decisions used FPFHSS-MULTIMOORA to address sustainability under technical, economic, and environmental criteria [191].

A PDHHFL-MULTIMOORA model evaluated RV reducer information schemes using improved linguistic term comparison and distance measures for ranking accuracy [192]. Finally, UAV decisions under uncertainty were enhanced using DHFS-entropy-based MULTIMOORA, confirming ranking resilience via RS, RPA, and FMF views [193]. Through all these domain-spanning implementations, MULTIMOORA consistently delivers precise, transparent, and technically sound decision support by synthesizing mathematical normalization, robust aggregation techniques, and flexible data structures suited for both crisp and fuzzy environments. Table 1 representing the application of MULTIMOORA methods in different-different fields.

Table 1: Application of MULTIMOORA method.

Methods	Applications	Formulations / Contribution	Ref.
MOORA	Privatization decisions in transition economies	RS with normalization and RPA for ranking privatization alternatives	[117]
MOORA	Contractor ranking in project procurement	Normalized decision matrix, RS + RPA for stable multi-criteria contractor evaluation	[118]
MOORA	Road design alternatives optimization	Normalization of multi-objective decision matrix, RS, reference point for balancing economic, technical, and social criteria	[119]
MOORA + MULTIMOORA	Facilities sector decision-making	Combined RS, reference point, and FMF; tested robustness and stability of rankings	[120]
MULTIMOORA	Ranking heating losses in buildings	Used RS, reference point, multiplicative form; applied to energy efficiency in buildings	[121]
MULTIMOORA	Project management in transition economies	Applied MULTIMOORA framework for ranking projects; highlighted applicability in complex economic transitions	[122]
MULTIMOORA	Case study: Tanzania development priorities	Tested robustness of MULTIMOORA with socio-economic data, validated stable objective rankings	[123]
MULTIMOORA	General multi-objective optimization	Formal robustness analysis of MULTIMOORA combining ratio, reference point, and multiplicative form into one unified method	[124]
MULTIMOORA-FG (linguistic)	Personnel selection	Introduced fuzzy linguistic reasoning into MULTIMOORA; combined with preference aggregation for handling qualitative data	[125]
MULTIMOORA (Survey)	Review of developments and applications	Survey of theoretical progress and applications; analyzed robustness, extensions (fuzzy, interval, entropy-based)	[126]
Comprehensive MULTIMOORA	Biomedical material selection	Integrated target-based attributes with significant coefficients for weighted evaluation of materials	[127]
Fuzzy Entropy-weighted MULTIMOORA	Materials selection	Applied fuzzy entropy weights for objective importance allocation; handled uncertainty in data	[128]
Extended MULTIMOORA (Shannon entropy)	Materials selection	Used Shannon entropy for weight determination; reduced subjectivity in criteria weighting	[129]
Interval MULTIMOORA	Materials selection	Incorporated interval numbers in decision matrix; avoided data degradation; interval entropy & preference matrix for ranking	[130]
MULTIMOORA + MOOSRA	Laptop selection	Compared MULTIMOORA and MOOSRA for consumer electronics decision-making; highlighted consistency in rankings	[131]
MULTIMOORA + Circular q-rung orthopair fuzzy sets	College students' mental health assessment	Integrated fuzzy q-rung orthopair means with MULTIMOORA to handle uncertainty in psychological evaluation	[132]
MULTIMOORA + Picture fuzzy decision framework	Higher education physical education quality	Combined picture fuzzy Muirhead mean operator with MULTIMOORA for educational performance assessment	[133]

Risk-based MULTIMOORA (information theory)	Gas turbine material selection	Risk-based evaluation using entropy and MULTIMOORA; balanced technical and risk factors	[134]
Probabilistic Linguistic MULTIMOORA	Multi-criteria decision-making	Introduced probabilistic linguistic expectation function with improved Borda rule to refine aggregation	[135]
MULTIMOORA + Shannon Entropy	Performance appraisal method selection	Integrated entropy weighting with MULTIMOORA for objective and consistent ranking	[136]
Overview of MULTIMOORA	Theory, developments, applications	Provided comprehensive review; discussed extensions (fuzzy, interval, entropy, linguistic, neutrosophic) and future challenges	[137]
Bipolar Fuzzy MULTIMOORA	Multi-criteria decision-making	Extended MULTIMOORA under bipolar fuzzy sets; handled positive/negative evaluations simultaneously	[138]
Distance-based Intuitionistic Multiplicative MULTIMOORA	Group decision-making	Integrated distance measure with multiplicative form; new weight-determining method for improved aggregation	[139]
Neutrosophic MULTIMOORA + SWARA	Internal combustion engine energy–ecological analysis	Combined MULTIMOORA with SWARA weighting; handled neutrosophic uncertainty in ecological parameters	[140]
Interval MULTIMOORA + BWM & Borda Rule	Hybrid vehicle engine selection	Integrated interval BWM for criteria weighting and interval Borda rule for ranking; robust interval decision model	[141]
Extended MULTIMOORA (Interval Type-2 Fuzzy)	Failure mode risk prioritization	Used interval type-2 fuzzy sets for handling deep uncertainty in FMEA analysis	[142]
MULTIMOORA + FMEA (Trapezoidal neutrosophic)	Surgical risk evaluation	Combined FMEA with neutrosophic MULTIMOORA to evaluate healthcare risks under uncertain conditions	[143]
Neutrosophic MULTIMOORA (Trapezoidal)	Group decision-making	Applied trapezoidal neutrosophic numbers with MULTIMOORA to solve MAGDM problems	[144]
MULTIMOOSRAL (Integrated)	Supplier selection	Developed new hybrid (MULTIMOORA + MOOSRA + linear additive ranking) for robust supplier evaluation	[145]
MULTIMOORA + TOPSIS + WASPAS	University location selection	Proposed hybrid MCDM combining MULTIMOORA with TOPSIS/WASPAS for site evaluation	[146]
CRITIC–MULTIMOORA (Neutrosophic)	Warehouse manager selection	Applied CRITIC for objective weighting and neutrosophic MULTIMOORA for robust personnel decision	[147]

Improved MULTIMOORA (Prospect theory, Neutrosophic)	Group decision-making	Introduced behavioral prospect theory into neutrosophic MULTIMOORA to reflect decision-makers' risk attitudes	[148]
Fuzzy AHP + Fuzzy MULTIMOORA	Supply chain risk-benefit assessment & supplier selection	Combined fuzzy AHP for weighting with fuzzy MULTIMOORA for final ranking	[149]
D-numbers MULTIMOORA	Risk evaluation of CCUS projects	Integrated D-numbers theory with MULTIMOORA to manage uncertainty in carbon capture project risk assessment	[150]
Extended MULTIMOORA (Trapezoidal Fuzzy Neutrosophic + Objective weighting)	Group decision-making	Combined trapezoidal neutrosophic sets with objective weighting method for robust group ranking	[151]
HF-AHP–MULTIMOORA	Gas-fired combi boiler evaluation	Used HF-AHP for weighting and MULTIMOORA for ranking; applied to household energy efficiency	[152]
Evidential MULTIMOORA (Linguistic)	Disaster risk reduction education	Applied evidential reasoning under linguistic uncertainty within MULTIMOORA	[153]
Improved Fuzzy MULTIMOORA	Ship risk assessment	Applied fuzzy MCDM based on MULTIMOORA for operational risk prioritization in maritime context	[154]
MOORA + FMF (Extended)	Mining method selection	Introduced spherical fuzzy linguistic sets into MOORA + multiplicative form for mining decision problems	[155]
Pythagorean Fuzzy MULTIMOORA	New product development	Applied Pythagorean fuzzy MULTIMOORA to evaluate product innovation strategies	[156]
Bipolar Pythagorean Neutrosophic MULTIMOORA	Decision-making problems	Extended MULTIMOORA to bipolar Pythagorean neutrosophic sets for uncertainty handling	[157]
Pythagorean Fuzzy MULTIMOORA (Schweizer–Sklar operations)	CO_2 geological storage site selection	Integrated fuzzy Schweizer–Sklar operators with MULTIMOORA for energy site evaluation	[158]
Weighted MULTIMOORA (weighting technique impact study)	Patient ranking using medical data	Analyzed how weighting techniques affect MULTIMOORA ranking consistency with ambiguous data	[159]
Regret Theory–based MULTIMOORA (Interval Neutrosophic)	Multi-criteria decision-making	Incorporated regret theory into neutrosophic MULTIMOORA to reflect human decision biases	[160]

Improved Fuzzy MULTIMOORA	Welding process selection	Developed modified fuzzy MULTIMOORA framework for industrial process evaluation	[161]
Hybrid MCDM (includes MULTIMOORA)	Quality function deployment	Analytical review of MCDM–QFD integration including MULTIMOORA applications	[162]
MULTIMOORA	Brake pad performance (red mud reinforced)	Applied classical MULTIMOORA for ranking mechanical performance in automotive materials	[163]
MULTIMOORA–WASPAS + q-rung orthopair fuzzy	Assessment of S3PRLPs (supply chain resilience)	Integrated WASPAS with q-rung orthopair fuzzy MULTIMOORA for resilience evaluation	[164]
Consensus-Based MULTIMOORA (Probabilistic Hesitant Fuzzy)	Manufacturing vendor selection	Developed consensus-based MULTIMOORA under hesitant fuzzy environment for group decision-making	[165]
Spherical fuzzy BWM + MULTIMOORA	Smart electric bus charging station siting	Spherical fuzzy sets for uncertainty; BWM for weights; MULTIMOORA (ratio, reference, multiplicative) for final ranking	[166]
Extended MULTIMOORA + evidential reasoning	Cognitive analysis in medical decision-making	Multigranulation probabilistic fusion; evidence theory for ambiguity; extended MULTIMOORA for stable ranking	[167]
PIPRECIA-S + MULTIMOORA	Personnel selection in group decision-making	PIPRECIA-S for stable expert weights; MULTIMOORA for candidate ranking with sensitivity analysis	[168]
Survey of MOORA/MULTIMOORA & fuzzy variants	Methodological review	Comparative taxonomy (interval, intuitionistic, neutrosophic, q-ROF, etc.); insights on weighting and ranking stability	[169]
MULTIMOORA	Turkish container port assessment	Indicator normalization; tri-method MULTIMOORA ranking for composite performance	[170]
Interval-valued fuzzy MULTIMOOSRAL	Supplier evaluation in oil projects	Interval fuzzy numbers for imprecision; hybrid ratio/multiplicative + MOOSRA-style integration	[171]
Integrated MCDM–MCDA	Agricultural crop economics	Multi-criteria framework combining weighting & ranking; compares/aggregates outcomes for crop decisions	[172]
IT2FS-MULTIMOORA + improved Borda	SME credit rating in supply-chain finance	IT2FS for hesitancy; correlation-based weights; improved Borda & extended reference-point for ranking stability	[173]
AHP–MULTIMOORA with decomposed fuzzy sets	Post-earthquake infectious disease risk	Decomposed fuzzy modelling; AHP subjective weights; MULTIMOORA for scenario prioritization	[174]

Pythagorean linguistic + quantum GDM + MULTIMOORA	Green supplier selection	Pythagorean linguistic sets for judgments; quantum consensus; MULTIMOORA tri-ranking fusion	[175]
Extended MULTIMOORA (with rough-Z numbers)	PV recycling center location	Sustainability criteria; rough-Z uncertainty; extended MULTIMOORA for robust siting	[176]
PULTS + Regret Theory + MULTIMOORA	Decision strategy evaluation	Probabilistic linguistic (PULTS) with new distance; BWM for weights; Regret-Theory aggregation; MULTIMOORA ranking	[177]
MULTIMOORA	SDG performance in Indonesia	Normalization of SDG indicators; three sub-methods for comparative temporal ranking	[178]
Fuzzy DANP + Fuzzy MULTIMOORA	Renewable energy source ranking (Isfahan, Iran)	Fuzzy DANP for causal weights; fuzzy MULTIMOORA for ratio/reference/multiplicative rankings	[179]
Picture fuzzy + Muirhead mean + generalized MULTIMOORA	Higher education PE quality	Picture fuzzy numbers for uncertainty; Muirhead mean for interaction; generalized MULTIMOORA ranking	[180]
Likelihood Interval-Valued Intuitionistic Fuzzy DNMEREC–MULTIMOORA	Enterprise green technology investment	Likelihood-based interval intuitionistic fuzzy numbers; DNMEREC for weights; MULTIMOORA for final ranking	[181]
MULTIMOORA	OECD countries health system performance	Normalized indicators; tri-method MULTIMOORA ranking for cross-country comparison	[182]
MCDM (comparative methods)	Optimal gold mining site selection (Ghana)	Integrated multi-criteria decision-making to compare and select optimal mining sites	[183]
MULTIMOORA	HVAC system energy retrofit	Ratio, reference, multiplicative forms of MULTIMOORA for private/public interest evaluation	[184]
Signless Laplacian + group decision MULTIMOORA	Graph-based energy analysis	Intuitionistic fuzzy graph energy analysis combined with group decision MULTIMOORA	[185]
Decomposed fuzzy + metaheuristic + MULTIMOORA	UAV selection in agriculture	Fuzzy decomposition for criteria; metaheuristic for search; MULTIMOORA for final multi-criteria ranking	[186]
MULTIMOORA	WHO European region NCD indicators comparison	Normalized multi-criteria evaluation; tri-method MULTIMOORA ranking for country performance	[187]

Two-stage MCDM + Q-rung orthopair fuzzy sets + MULTIMOORA	Railway freight logistics efficiency	QROF sets for uncertainty; two-stage ranking integrating MULTIMOORA for logistics optimization	[188]
MULTIMOORA	Power generation technology selection	Ratio, reference, multiplicative forms for MCDM in energy sector	[189]
MULTIMOORA	ESG risk-taking assessment (Warsaw Stock Exchange)	Multi-criteria evaluation of ESG risks; classical MULTIMOORA for ranking companies	[190]
Fuzzy parameterized fuzzy hypersoft set + MULTIMOORA	Wastewater treatment performance	Fuzzy hypersoft sets for uncertain criteria; MULTIMOORA tri-ranking for treatment options	[191]
Probability Double Hierarchy Hesitant Fuzzy Term Set + MULTIMOORA	General MCDM problem	Combined hierarchical hesitant fuzzy term sets with MULTIMOORA for ranking alternatives	[192]
Dual hesitant fuzzy sets + MULTIMOORA	UAV selection	Dual hesitant fuzzy set aggregation; MULTIMOORA for final multi-criteria ranking	[193]

Multi-objective optimization is essential for enhancing performance in engineering and energy systems. In machining, Taguchi design with Grey Relational Analysis optimized tool life and surface finish of AISI 4340 alloy steel, where CVD (Chemical vapor deposition) tools gave maximum tool life and PVD (Physical vapor deposition) tools improved surface quality. Feed rate was the most influential parameter [196]. In wind turbine gearboxes, NSGA-II minimized weight and power loss under scuffing constraints. PAO 680 oil provided the best efficiency and durability, confirming that optimization reduced energy losses while maintaining reliability [197]. For titanium alloys, Carbon nanotubes (CNT) based nano-lubricants improved friction and wear resistance. Taguchi analysis showed SWCNT (Single walled carbon nano tubes) reduced friction variability, while MWCNT minimized wear variability. Load had the strongest effect, followed by sliding speed [198]. Mathematical modelling of lubricant flow demonstrated that optimizing sliding bearings in the 4–8 MPa hydrodynamic pressure range reduced the friction coefficient significantly. Application of low-melting alloy coatings further minimized losses [199]. These studies show the effectiveness of different multi-objective optimization methods in solving tribological challenges. Optimization methods such as Taguchi, GRA, and MULTIMOORA have been successfully applied in related works. In a similar approach, Botryococcus braunii based bio-nanolubricant formulations with hybrid nano-additives can be optimized using the MULTIMOORA method, balancing tribological and physicochemical properties for maximum efficiency, durability, and sustainability.

1.8 Originality of the Work

The novelty of this research is the first to apply the MULTIMOORA method for optimizing *Botryococcus braunii*-based bio-nanolubricant formulations enhanced with hybrid nano-additives. Unlike conventional optimization techniques, MULTIMOORA can handle multiple, often conflicting, performance parameters such as viscosity, friction reduction, and thermal stability simultaneously and objectively. This ensures a more balanced and reliable selection of lubricant compositions. The approach provides a new, systematic, and accurate way to identify the most effective and eco-friendly bio-nanolubricant formulations, improving both performance and sustainability.

2.0 MATERIALS AND METHODOLOGY

Bionanolubricants were prepared using Botryococcus braunii microalgae oil blended with surfactants and nano-additives. Key properties like viscosity, density, thermal, and dispersion stability were tested. Friction and wear were evaluated through tribological tests. The MULTIMOORA method played a central role in analysing all results to identify the most effective lubricant formulation with the help of attributes.

2.1 Materials

Botryococcus braunii microalgae was collected from Bhalswa Lake, Delhi, and processed using lab-grade chemicals from IGDTUW. Nano-additives like Al_2O_3 (Aluminium oxide), GO (Graphene oxide), TiO_2 (Titanium oxide) and MWCNTs (Microwalled carbon nanotubes) were sourced from Platonic Pvt. Ltd. Materials for pin and disc came from Chawri Bazaar, while surfactant oleic acid and other chemicals were bought from Tilak Bazaar. All reagents used were of analytical grade.

2.1 Production of Botryococcus Braunii Microalgae Lubricant

Botryococcus braunii microalgae was collected from Bhalswa Lake, Delhi, and cultivated in CHU-13 medium under controlled lab conditions. The culture was maintained at 25 °C, pH 7.5, under 150 μmol photons m^{-2} s^{-1} LED light (600 nm) with a 16:8 h light–dark cycle. After growth, the biomass was harvested by centrifugation (11,000 rpm), filtered using Whatman paper, rinsed thrice, and freeze-dried. Growth was monitored by gravimetric analysis (dry weight). Lipids were extracted using Soxhlet with n-hexane after 45 min sonication and measured gravimetrically. For transesterification, extracted lipids were treated with NaOH (0.016 g/kg oil) as a catalyst at 50 °C and 800 rpm. The reaction was run for 80–240 min with samples taken at intervals, and 140 min was found optimal for maximum yield. Various oil-to-methanol molar ratios (1:5 to 1:10) were tested, with 1:7 yielding >93% methyl ester conversion. The product was purified by washing with 1 wt% H_3PO_4 in deionized water, dried with anhydrous Na_2SO_4, centrifuged at 8000 rpm for 10 min, and the oil phase collected. Final yield was determined using gravimetric analysis.

2.2 Preparation of Bionanolubricants

In this study, bionanolubricants were developed by incorporating hybrid nano-additives into *Botryococcus braunii* microalgae oil. A total of eight samples were prepared, six with different nano-additive blends, one with pure *B. braunii* oil, and one with commercial 20W40 oil (SAE standard) for comparison. Oleic acid (1%) was used as a surfactant in all modified formulations to ensure proper dispersion and stability of nano-additives. Nano-additives were precisely weighed using a high-precision analytical balance (0.1 mg readability, electromagnetic force compensation). The additives were then mixed with microalgae oil and oleic acid using a magnetic stirrer at 1400 RPM for 40 minutes. The stirrer had a ceramic-coated plate resistant to chemicals and could reach up to 280 °C, with temperature monitored by a PT1000 sensor (±0.5 °C accuracy). Further homogenization was done using a probe sonicator at 70 °C for 60 minutes (4 cycles of 15 min with 30 s rest), operating at 20–25 kHz and power range 6.5–650 W, inside a soundproof enclosure. This ensured uniform and stable nano-additive dispersion. Dispersion stability was visually monitored over time (2–72 hours) to observe sedimentation, agglomeration, or phase separation. Consistent stability confirmed proper blending, which is essential for enhanced tribological and thermal performance of the bionanolubricants. Formulation description of samples can be seen in table 2 and physical representation of lubricant samples can be seen in Figure 2.

Table 2: Lubricant samples description based on constituents.

Sample Number	Lubricant Sample Name	Composition of Components in Samples (By Weight Percentage)
Sample 1	B100	100 % Pure Botryococcus Braunii Microalgae Oil
Sample 2	B99O1A0.5C0.5	99% Botryococcus Braunii Microalgae Oil + 1% Oleic Acid Surfactant+ 0.5% Al_2O_3 + 0.5% MWCNT
Sample 3	B99O1A0.5G0.5	99% Botryococcus Braunii Microalgae Oil + 1% Oleic Acid Surfactant + 0.5% Al_2O_3 + 0.5% GO
Sample 4	B99O1A0.5T0.5	99% Botryococcus Braunii Microalgae Oil + 1% Oleic Acid Surfactant + 0.5% Al_2O_3 + 0.5% TiO_2
Sample 5	B99O1T0.5G0.5	99% Botryococcus Braunii Microalgae Oil + 1% Oleic Acid Surfactant + 0.5% TiO_2 + 0.5% GO
Sample 6	B99O1T0.5C0.5	99% Botryococcus Braunii Microalgae Oil + 1% Oleic Acid Surfactant + 0.5% TiO_2 + 0.5% MWCNT
Sample 7	B99O1G0.5C0.5	99% Botryococcus Braunii Microalgae Oil + 1% Oleic Acid Surfactant + 0.5% GO + 0.5% MWCNT
Sample 8	20W-40	100 % Pure 20W-40 Oil

Figure2. Physical representation of formulated lubricant samples.

2.3 Evaluation of Physicochemical and Tribological Properties

The physicochemical properties of eight lubricant samples were tested using standard ASTM methods to ensure accuracy. Density at 15 °C was measured using a graduated cylinder (ASTM D4052), and kinematic viscosity at 100 °C was determined with a Stabinger viscometer (ASTM D7042). Flash point was tested using a Flash Point Apparatus (ASTM D92), while pour point and cloud point were measured as per ASTM D97 and ASTM D2500. Acid value was evaluated using potentiometric titration (ASTM D664). All instruments were calibrated with standard lubricants before testing. These tests helped assess thermal stability, flow behavior, and oxidation resistance of the bionanolubricants. Eight samples were tested for tribological performance using a Pin-on-Disc Tribometer, following ASTM G99 standards. The test measured coefficient of friction, wear (in µm), and specific wear rate ($\times 10^{-3}$ mm^3/N-m) to evaluate lubrication efficiency and durability. The tribometer simulated real sliding conditions to study friction and wear behaviour. This setup ensured precise assessment of anti-wear properties under controlled laboratory conditions.

2.4 MULTIMOORA Method

MULTIMOORA (Multi-Objective Optimization by Ratio Analysis plus Full Multiplicative Form), developed by Brauers and Zavadskas in 2010, is a powerful Multi Criteria Decision Making method. It combines three tools RS, RPA, and FMF to evaluate alternatives with multiple, often conflicting goals. This integration improves objectivity and makes it ideal for complex decision-making situations [121].

2.5 The Ratio System (RS)

This component of MOORA (introduced by Brauers and Zavadskas in 2006) starts by constructing a decision matrix $X = x_{ij}$, where x_{ij} represents the performance of the j^{th} alternative on the i^{th} objective. The matrix is then internally normalized using the following formula [121].

$$x_{ij}^{*} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{m} x_{ij}^{2}}}$$

This normalization renders each element dimensionless, ensuring comparability across different units. For optimization, the normalized values corresponding to maximization objectives (from $i = 1$ to g) are summed, and those corresponding to minimization objectives (from $i = g + 1$ to n) are subtracted [121].

$$y_j = \sum_{i=1}^{g} x_{ij}^{*} - \sum_{i=g+1}^{n} x_{ij}^{*}$$

The alternatives are then ranked based on the values of y_j with higher values indicating better performance [121].

2.6 The Reference Point Approach (RPA)

This approach also uses the normalized matrix x_{ij}^{*} from the RS. Here, a reference point r_i is established for each objective, typically representing the best performance across all alternatives [121].

$$r_i = \max_{j}\left(x_{ij}^{*}\right) \text{ for benefit-type objectives}$$

The Tchebycheff distance metric (also known as the min–max metric) is used to measure the distance of each alternative from this ideal reference point [121].

$$d_j = \max_{i}\left|x_{ij}^{*} - r_i\right|$$

The alternative with the smallest distance d_j to the reference point is considered the most preferable [121].

2.7 The Full Multiplicative Form (FMF)

This component captures interactions between criteria in a non-linear, non-additive format. The utility for each alternative j is computed as the product of its normalized performance scores [121].

$$U_j = \prod_{i=1}^{n} x_{ij}$$

To accommodate mixed objective problems (i.e., containing both maximization and minimization criteria), the formula is partitioned into two parts [121].

For objectives to maximize,

$$A_j = \prod_{i=1}^{g} x_{ij}$$

For objectives to minimize,

$$B_j = \prod_{i=g+1}^{n} x_{ij}$$

The overall utility is then,

$$U'_j = \frac{A_j}{B_j}$$

This approach ensures that objectives to be minimized appropriately penalize the overall utility score [121].

2.8 Final Ranking by MULTIMOORA

MULTIMOORA uses three methods RS, RPA, and FMF to rank alternatives. These rankings are then combined using techniques like dominance theory, majority rule or Borda count to create one final, reliable ranking. This multi-angle approach boosts accuracy and decision confidence. MULTIMOORA offers several advantages: it performs unit-free comparisons, supports both additive and multiplicative models, doesn't require subjective weights (unless chosen), and works well in uncertain or complex situations. It's widely applicable in fields like engineering, energy, logistics, and economics. MULTIMOORA method is taken for the optimization in this study for its qualities like very less computational time, very simple, minimum mathematical calculations, stability is good, quantitative method [121]. In this study attributes and objectives of all alternatives for MULTIMOORA optimization are Density @ 15^{o}C (g/cm^{3}), Kinematic Viscosity @ 100^{o}C (mm^{2}/s), Flash Point (^{o}C), Pour Point (^{o}C), Cloud Point (^{o}C), Acid Value (mg KOH/g), Coefficient of Friction, Wear (micron) and Specific Wear Rate (10^{-3} mm^{3}/N-m) shown in table 3 and 4. The objective of this investigation is to develop a decision making for evaluating and selecting bionanolubricant formulations using multi-criteria optimization method MULTIMOORA. Each alternative represents a unique bionanolubricant formulation, and their performance is assessed based on the nine attributes listed in Table 3. Some attributes are to be maximized (density, viscosity and flash point), while others are to be minimized (Pour Point, Cloud Point, Coefficient of Friction, Specific Wear Rate, wear and acid value). The RS, Reference Point, and FMF of the MULTIMOORA method were applied to derive an objective ranking of the bionanolubricant alternatives. The final ranking of the bionanolubricants was then determined using the dominance theory, consolidating the rankings from each approach to ensure a robust and balanced evaluation. This application of MULTIMOORA allows for a comprehensive and unbiased assessment of various bionanolubricant formulations by simultaneously considering their tribological and physicochemical performance. Such a technique is particularly useful in formulating advanced lubricants for industrial and automotive use, where performance and sustainability are critical considerations.

Table 3: Main attributes and objectives of bionanolubricant samples.

Attributes	**Units of measurement**	***max/min***	**Objectives**
Density @ 15°C	g/cm^3	*max*	x_1
Kinematic Viscosity @ 100°C	mm^2/s	*max*	x_2
Flash Point	°C	*max*	x_3
Pour Point	°C	*min*	x_4
Cloud Point	°C	*min*	x_5
Acid Value	mg KOH/g	*min*	x_6
Coefficient of Friction	-	*min*	x_7
Wear	micron	*min*	x_8
Specific Wear Rate	10^{-3} mm^3/N-m	*min*	x_9

Table 4: Alternatives of objectives of bionanolubricant samples.

Bionanolubricant Samples	**Alternatives**
B100	A_1
B99O1A0.5C0.5	A_2
B99O1A0.5G0.5	A_3
B99O1A0.5T0.5	A_4
B99O1T0.5G0.5	A_5
B99O1T0.5C0.5	A_6
B99O1G0.5C0.5	A_7
20W-40	A_8

2.9 Validation Method VIKOR

For the validation of optimize result of MULTIMOORA method VIKOR method is used in this study. VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) is also a multi-criteria decision-making (MCDM) method. It helps rank alternatives (samples, projects, products, etc.) when there are multiple conflicting criteria. VIKOR works by Normalizing the criteria values so they're comparable, Calculating S (overall performance) and R (worst-case performance) for each alternative, combining them into a single Q index (VIKOR index) to rank the options [195].

2.10 Normalize the Decision Matrix

For each criterion *j*,

X_j^* = best value among all alternatives and X_j^- = worst value among all alternatives

For a benefit criterion (larger is better),

$$R_{ij} = \frac{X_j^* - X_{ij}}{X_j^* - X_j^-}$$

For a cost criterion (smaller is better),

$$R_{ij} = \frac{X_{ij} - X_j^*}{X_j^- - X_j^*}$$

R_{ij} is the normalized "distance" from the best value for alternative *i* on criterion *j*.

2.11 Calculate *S* and *R* values

S_i = overall gap from the ideal solution (weighted sum of normalized distances),

$$S_i = \sum_{j=1}^{n} w_j \cdot R_{ij}$$

R_i = worst gap on any single criterion (weighted max of normalized distances),

$$R_i = \max_j \left[w_j \cdot R_{ij} \right]$$

w_j = weight of criterion j

2.12 Calculate the VIKOR Index Q_i

Use S' = smallest S (best), S^* = largest S (worst), R' = smallest R (best), R^* = largest R (worst)

$$Q_i = V \cdot \frac{S_i - S'}{S^* - S'} + (1 - V) \cdot \frac{R_i - R'}{R^* - R'}$$

V is the weight of the majority rule
Sort alternatives by Q (lowest = best compromise) [195].

3.0 EXPERIMENTAL SETUP

The tribological performance of all eight lubricant samples was evaluated using a high-temperature Pin-on-Disc Tribometer, following ASTM G99 standards. The tribometer was calibrated with a standard lubricant before testing. Each test was conducted at a sliding speed of 500 rpm, under a maximum normal load of 200 N, covering a sliding distance of 1000 m over 13 minutes per sample. Each lubricant sample was tested in triplicate to ensure repeatability. A new mild steel pin (10 mm diameter, 30 mm length) was used for every test. The rotating disc was made of EN31 steel with a maximum track diameter of 100 mm, though a fixed track diameter of 50 mm was used for consistency. The pin remained stationary while the disc rotated beneath it, simulating real sliding contact conditions. Before each test, all components were cleaned with ethanol and dried. Exactly 10 ml of lubricant was applied in dropwise form to the contact area. After each run, pins and discs were cleaned with acetone. The disc surface was polished to a mirror finish before reuse. The wear and friction data were acquired using analytic software. The pin's wear rate was determined gravimetrically by weighing it before and after testing using a precision balance, with samples stored in a vacuum oven to prevent oxidation.

4.0 RESULTS AND DISCUSSION

This section presents the optimization of bionanolubricants using the MULTIMOORA method based on key performance attributes. Physicochemical tests evaluated density, viscosity, flash point, pour point, cloud point, and acid value, providing insight into thermal stability and flow behavior and Dispersion stability tests assessed how well nano-additives remained suspended over 72 hours. Tribological tests measured coefficient of friction, wear and specific wear rate. These results were analyzed using the MULTIMOORA method to rank all samples and identify the most effective lubricant formulation. The findings highlight the performance, durability, and application potential of optimized *Botryococcus braunii* based bionanolubricants.

4.1 Physicochemical and Tribological Properties of Lubricant Samples

The *Botryococcus braunii* lipid extract had an average molecular weight of 920 g/mol and a lipid content of 53.9 wt.%, offering excellent thermal stability and biodegradability for eco-friendly lubricant formulations. Eight bionanolubricant samples were evaluated based on key parameters density, kinematic viscosity at 100 °C, flash point, pour point, cloud point and acid value. All samples showed strong dispersion stability without sedimentation, agglomeration or phase separation over 72 hours, the samples were visually monitored from 0 to 72 hours at regular intervals of 8 hours to observe any changes over time. Bionanolubricant samples B99O1A0.5C0.5, B99O1T0.5C0.5 and B99O1G0.5C0.5 showed a greasy texture immediately after preparation, indicating higher viscosity and potential for enhanced boundary lubrication. Tribological performance was tested under a maximum 200 N load using a Pin-on-Disc Tribometer with parameters coefficient of friction, wear and specific wear rate ($\times 10^{-3}$ mm^3/N-m) measured Table 5 represents all these Physicochemical and Tribological properties. Each sample was tested in triplicate, and standard deviation was calculated to ensure reliability. The standard SAE-grade 20W-40 lubricant was tested as a benchmark for comparison with the seven bio-nanolubricant samples. Its experimentally evaluated physicochemical properties matched well with those reported in [194], confirming its reliability. The tribological performance of 20W-40 served as a reference point to evaluate the efficiency of the newly developed formulations under identical test conditions. The consistent physicochemical properties and stable tribological behavior across all samples confirm their suitability for automotive and industrial applications, offering reduced friction, improved wear resistance and greater energy efficiency.

Table 5: Physiochemical and tribological properties of Bio-nanolubricants.

Physiochemical Properties	B100	B99O1A 0.5C0.5	B99O1A 0.5G0.5	B99O1A 0.5T0.5	B99O1T 0.5G0.5	B99O1T 0.5C0.5	B99O1G 0.5C0.5	20W 40
Density @ 15°C (g/cm^3)	0.898	0.922	0.879	0.909	0.901	0.921	0.925	0.876
Kinematic Viscosity @ 100°C (mm^2/s)	4.70	20.50	5.60	7.30	6.90	20.40	21.30	15.10
Flash Point (°C)	114.0	242.0	183.0	207.0	196.0	238.0	259.0	235.0
Pour Point (°C)	-15.0	-46.0	-32.0	-37.0	-35.0	-43.0	-48.0	-21.0
Cloud Point (°C)	-3.0	-13.0	-8.0	-9.0	-10.0	-13.0	-13.0	-11.0
Acid Value (mg KOH/g)	0.31	0.227	0.251	0.178	0.235	0.256	0.219	0.637
Coefficient of Friction	0.586	0.43	0.488	0.397	0.261	0.445	0.277	0.363
Wear (micron)	71.001	152.177	199.087	56.518	217.828	151.281	37.082	104.906
Specific Wear Rate (10^{-3} mm^3/N-m)	0.0101	0.0329	0.0143	0.0066	0.0172	0.0332	0.0027	0.0265

Botryococcus braunii algae oil provides key advantages as a base for eco-friendly lubricants. Its high lipid content (around 54 %) and molecular weight contribute to natural stability for lubrication of machine parts. The oil inherently supports better chemical stability and oxidation resistance, reducing the need for synthetic additives. Its compatibility with nanoadditives allows the formulation of lubricants that can achieve enhanced load bearing and surface protection. It serves as a sustainable and high-performance alternative for industrial and automotive lubrication.

The formulated bio-nanolubricants were compared against commercial 20W-40 lubricant to evaluate their performance. In terms of density, all samples showed slightly higher values than 20W-40 (0.876 g/cm^3), with B99O1G0.5C0.5 being the highest (0.925 g/cm^3), due to the denser structure of hybrid nanoadditives like GO and MWCNT. Kinematic viscosity at 100°C was significantly improved in B99O1A0.5C0.5 (20.50 mm^2/s), B99O1T0.5C0.5 (20.40 mm^2/s) and B99O1G0.5C0.5 (21.30 mm^2/s), surpassing 20W-40 (15.10 mm^2/s), which enhances load-bearing capacity due to strong nanoparticle base lubricant interactions that resist shear thinning. Flash point increased in all samples, with B99O1G0.5C0.5 reaching 259°C compared to 235°C for 20W-40, indicating better thermal stability, particularly due to the thermal resistance of GO and MWCNT. Pour point was significantly lower in all bio-nanolubricants, especially B99O1G0.5C0.5 at -48°C vs -21°C in 20W 40, showing superior low-temperature flow, attributed to nanoadditives disrupting crystallization. Cloud points followed similar trends, with most samples at -13°C, better than 20W 40's -11°C, enhancing cold start performance. Acid value was markedly lower in all samples, especially B99O1A0.5T0.5 (0.178 mg KOH/g) vs 0.637 in 20W-40, implying enhanced oxidation resistance and chemical stability due to antioxidant behaviour of TiO_2 and GO. Coefficient of friction dropped significantly, with B99O1T0.5G0.5 (0.261) and B99O1G0.5C0.5 (0.277) showing the best reduction compared to 0.363 in 20W-40, due to tribofilm formation and rolling effect from spherical and layered nanoparticles. Wear scar depth was also lowest in B99O1G0.5C0.5 (37.082 μm) vs 104.906 μm in 20W-40, thanks to the synergistic mending and protective effects of GO and MWCNT. Specific wear rate was best in B99O1G0.5C0.5 (0.0027×10^{-3} mm^3/N-m), nearly one-tenth of 20W-40 (0.0265×10^{-3} mm^3/N-m), confirming its superior anti-wear behaviour. Experimentally B99O1G0.5C0.5 outperformed all samples and the benchmark bionanolubricant due to the synergistic lubricating, surface-protective, and thermal properties of GO and MWCNT, while B100 showed the weakest performance due to the absence of nanoadditives.

4.2 Application of MULTIMOORA Method

The RS, the reference point and The full Multiplicative Form approach as a part of MULTIMOORA calculations has been done one the basis of attributes and alternatives can be seen in table 6, 7, 9. The final evaluations are shown in the tables. Table 8 shows the RS results, Table 10 shows the reference point results, and Table 11 shows the MULTIMOORA method results. Table 12 gives the final ranking of the bionanolubricants.

Table 6: Initial decision matrix showing the responses of alternatives for each objective.

Alternatives ↓	**Objectives →**								
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
	max	***max***	***max***	***min***	***min***	***min***	***min***	***min***	***min***
A_1	0.898	4.7	114	-15	-3	0.31	0.586	71.001	0.0101
A_2	0.922	20.5	242	-46	-13	0.227	0.43	152.177	0.0329
A_3	0.879	5.6	183	-32	-8	0.251	0.488	199.087	0.0143
A_4	0.909	7.3	207	-37	-9	0.178	0.397	56.518	0.0066
A_5	0.901	6.9	196	-35	-10	0.235	0.261	217.828	0.0172
A_6	0.921	20.4	238	-43	-13	0.256	0.445	151.281	0.0332
A_7	0.925	21.3	259	-48	-13	0.219	0.277	37.082	0.0027
A_8	0.876	15.1	235	-21	-11	0.637	0.363	104.906	0.0265

Table 7: Sum of squares and their square root values.

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
A_1	0.8064	22.09	12996	225	9	0.0961	0.3433	5041.14	0.0001
A_2	0.8500	420.25	58564	2116	169	0.0515	0.1849	23157.8393	0.0010
A_3	0.7726	31.36	33489	1024	64	0.0630	0.2381	39635.6335	0.0002
A_4	0.8262	53.29	42849	1369	81	0.0316	0.1576	3194.2843	0.00004
A_5	0.8118	47.61	38416	1225	100	0.0552	0.0681	47449.0375	0.0002

A_6	0.8482	416.16	56644	1849	169	0.0655	0.1980	22885.9409	0.0011
A_7	0.8556	453.69	67081	2304	169	0.0479	0.0767	1375.0747	0.000007
A_8	0.7673	228.01	55225	441	121	0.4057	0.1317	11005.2688	0.0007
Sum of Squares	6.5381	1672.46	365264	10553	882	0.8165	1.3984	153744.219	0.003347
Square Roots	2.5569	40.8957	604.3707	102.7277	29.6984	0.9036	1.1825	392.1023	0.0578

Table 8: Objectives divided by their square roots and used for MOORA analysis.

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	**Total**	**Rank**
A_1	0.3512	0.1149	0.1886	-0.1460	-0.1010	0.3430	0.4955	0.1810	0.1747	-0.7865	**3**
A_2	0.3605	0.5012	0.4004	-0.4477	-0.4377	0.2512	0.3636	0.3881	0.5692	-1.1954	**5**
A_3	0.3437	0.1369	0.3027	-0.3115	-0.2693	0.2777	0.4126	0.5077	0.2474	-1.2429	**8**
A_4	0.3555	0.1785	0.3425	-0.3601	-0.3030	0.1969	0.3357	0.1441	0.1141	-0.5774	**2**
A_5	0.3523	0.1687	0.3243	-0.3407	-0.3367	0.2600	0.2207	0.5555	0.2975	-1.1658	**4**
A_6	0.3602	0.4988	0.3937	-0.4185	-0.4377	0.2833	0.3763	0.3858	0.5743	-1.2232	**7**
A_7	0.3617	0.5208	0.4285	-0.4672	-0.4377	0.2423	0.2342	0.0945	0.0467	-0.2116	**1**
A_8	0.3426	0.3692	0.3888	-0.2044	-0.3703	0.7049	0.3069	0.2675	0.4584	-1.2118	**6**

Table 9: Reference point theory using ratio coordinates, where the reference point equals the maximum objective values.

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
r_i	0.3617	0.5208	0.4285	-0.4672	-0.4377	0.1969	0.2207	0.0945	0.0467

Table 10: Reference point theory showing deviations from the reference point.

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	**max**	**Rank min**
A_1	0.0105	0.4059	0.2399	0.3212	0.3367	0.1461	0.2748	0.0865	0.1280	0.4059	**3**
A_2	0.0012	0.0196	0.0281	0.0195	0.0000	0.0543	0.1429	0.2936	0.5225	0.5225	**7**
A_3	0.0180	0.3839	0.1258	0.1557	0.1684	0.0808	0.1919	0.4132	0.2007	0.4132	**4**
A_4	0.0062	0.3423	0.0860	0.1071	0.1347	0.0000	0.1150	0.0496	0.0674	0.3423	**2**
A_5	0.0094	0.3521	0.1042	0.1265	0.1010	0.0631	0.0000	0.4610	0.2508	0.4610	**5**
A_6	0.0015	0.0220	0.0348	0.0487	0.0000	0.0864	0.1556	0.2913	0.5276	0.5276	**8**
A_7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0454	0.0135	0.0000	0.0000	0.0454	**1**
A_8	0.0191	0.1516	0.0397	0.2628	0.0674	0.5080	0.0862	0.1730	0.4117	0.5080	**6**

Table 11: The full multiplicative form.

	1	**2**	**2.1**	**3**	**3.1**	**4**	**4.1**	**5**	**5.1**	**6**	**6.1**	**7**	**7.1**	**8**	**8.1**	**9**	**9.1**	**Rank**
	max	***max***	**2.1=1·2**	***max***	**3.1=2.1·3**	***min***	**4.1=3.1:4**	***min***	**5.1=4.1:5**	***min***	**6.1=5.1:6**	***min***	**7.1=6.1:7**	***min***	**8.1=7.1:8**	***min***	**9.1=8.1:9**	***max***

A_1	0.898	4.7	4.2206	114	481.1484	-15	32.07656	-3	10.69218	0.31	34.4909	0.586	58.85819	71.001	0.82897	0.0101	82.0762	**3**
A_2	0.922	20.5	18.901	242	4574.042	-46	99.4356	-13	7.6488	0.227	33.6951	0.43	78.3606	152.177	0.5149	0.0329	15.6504	**5**
A_3	0.879	5.6	4.9224	183	900.7992	-32	28.1499	-8	3.5187	0.251	14.0187	0.488	28.7268	199.087	0.14442	0.0143	10.0839	**8**
A_4	0.909	7.3	6.6357	207	1373.5899	-37	37.1240	-9	4.1248	0.178	23.1730	0.397	58.3702	56.518	1.0327	0.0066	156.4696	**2**
A_5	0.901	6.9	6.2169	196	1218.5124	-35	34.8146	-10	3.4814	0.235	14.8144	0.261	56.7601	217.828	0.2605	0.0172	15.1453	**6**
A_6	0.921	20.4	18.7884	238	4471.6392	-43	103.9916	-13	7.9993	0.256	31.2472	0.445	70.2184	151.281	0.4641	0.0332	13.9789	**7**
A_7	0.925	21.3	19.7025	259	5102.9475	-48	106.3114	-13	8.1778	0.219	37.3415	0.277	134.8068	37.082	3.6353	0.0027	1346.4074	**1**

A₈	0.876	15.1	13.2276	235	3108.486	-21	148.0231	-11	13.4566	0.637	21.1249	0.363	58.1953	104.906	0.5547	0.0265	20.9320	**4**

In the case study, MOORA and MULTIMOORA methods were used to rank the discrete alternatives. The three results obtained were from the MOORA RS, MOORA reference point, and MULTIMOORA. The final results are shown in Table 12.

Table 12: MULTIMOORA based on the MOORA method and the full multiplicative form.

Alternatives	MOORA RS	MOORA Reference point	Full Multiplicative Form	MULTIMOORA
A_1	3	3	3	**3**
A_2	5	7	5	**5**
A_3	8	4	8	**8**
A_4	2	2	2	**2**
A_5	4	5	6	**4**
A_6	7	8	7	**7**
A_7	1	1	1	**1**
A_8	6	6	4	**6**

The study compared eight bionanolubricant samples, including pure biolubricant (B100), blends with hybrid nanoadditives, and commercial 20W-40 oil. MULTIMOORA ranking showed that A_7 (B99O1G0.5C0.5) performed the best, followed by A_4 (B99O1A0.5T0.5) and A_1 (B100). The lowest rank was A_3 (B99O1A0.5G0.5). The top-performing sample, A_7, likely achieved better ranking because the combination of graphene oxide and MWCNTs nanoadditives improved lubrication, reduced friction, and enhanced thermal stability compared to other blends.

4.3 Application of Validation Method VIKOR

For validating the MULTIMOORA results, the VIKOR method was applied using the same decision matrix shown in Table 6. All steps of the VIKOR method has been applied shown in table 13 to find the robust ranking of bionanolubricants, which confirmed the MULTIMOORA rankings.

Table: 13 Normalized decision matrix.

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	S	R	Q	Rank
A_1	0.551	1	1	1	1	0.2876	1	0.1877	0.2426	0.6965	0.1111	1	**8**
A_2	0.0612	0.0482	0.1172	0.0606	0	0.1068	0.52	0.6368	0.9902	0.2823	0.11	0.6905	**3**

A_3	0.9388	0.9458	0.5241	0.4848	0.5	0.159	0.6985	0.8963	0.3803	0.6142	0.1051	0.9098	**7**
A_4	0.3265	0.8434	0.3586	0.3333	0.4	0	0.4185	0.1075	0.1279	0.324	0.0937	0.6405	**2**
A_5	0.4898	0.8675	0.4345	0.3939	0.3	0.1242	0	1	0.4754	0.4539	0.1111	0.8219	**5**
A_6	0.0816	0.0542	0.1448	0.1515	0	0.1699	0.5662	0.6318	1	0.3111	0.1111	0.7171	**4**
A_7	0	0	0	0	0	0.0893	0.0492	0	0	0.0154	0.0099	0	**1**
A_8	1	0.3735	0.1655	0.8182	0.2	1	0.3138	0.3752	0.7803	0.5585	0.1111	0.8987	**6**

To validate the MULTIMOORA MCDM comprising the RS, reference-point method and multiplicative form selected top alternatives (A_7 as rank-1, A_4 as rank-2) applied a composite VIKOR approach to the same decision matrix using identical criterion directions and equal weights. For each sub-method computed alternative scores and produced rankings the three rankings were aggregated. Then measured rank agreement using the Top 2 agreement metric. Based on these checks, conclude that A_7 is robustly the best composition of bionanolubricants. The MULTIMOORA method found that the B99O1G0.5C0.5 formulation has better stability, lower friction, and less wear. VIKOR analysis confirmed these results by validation. Compared to commercial 20W-40 oil, this bio-nanolubricant performs better in wear resistance and thermal stability. It is well suited for tough mechanical applications.

CONCLUSIONS

On the basis of above experimental and optimization study following conclusions can be made. Botryococcus braunii lipid extract had high thermal stability, biodegradability and very high lipid content, making it suitable for eco-friendly lubricants. Eight bionanolubricant samples were examined against commercial 20W-40 oil for physicochemical and tribological performance. All samples showed excellent dispersion stability for 72 hours without sedimentation or phase separation. Hybrid nanoadditives GO and MWCNT in bionanolubricant B99O1G0.5C0.5 increased the density, viscosity, flash point, and thermal stability of the bio-lubricants. Density rose by about 5.6% (0.876 → 0.925 g/cm^3), viscosity at 100 °C increased by approximately 41% (15.10 → 21.30 mm^2/s), and flash point improved by around 10.2% (235 → 259 °C). These improvements are due to the dense structure and strong interaction of GO and MWCNT with the base oil, which enhances thermal stability, load-bearing capacity, and forms protective tribofilms that reduce friction and wear. Low pour and cloud points improved cold start performance in all bio-lubricants compared to 20W-40. Acid values were lower, indicating better oxidation resistance and chemical stability. Coefficient of friction and wear rates were significantly reduced, especially in GO + MWCNT blends. B99O1G0.5C0.5 showed the best overall performance, with the lowest wear and highest load-bearing capacity. MULTIMOORA ranking placed B99O1G0.5C0.5 first, followed by B99O1A0.5T0.5 with B99O1A0.5G0.5 lowest. VIKOR validation confirmed B99O1G0.5C0.5 as the most effective, robust, and reliable formulation.

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