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Sustainable Machining: A Comprehensive Review of Vegetable Oil-Based Metalworking Fluids

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التشغيل المستدام: مراجعة شاملة لسوائل تشغيل المعادن القائمة على الزيوت النباتية

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Abstract:
The manufacturing area heavily relies on metalworking fluids (MWFs) to cool and lubricate the cutting zone, thereby enhancing tool life and surface finish. Historically, petroleum-based mineral oils have dominated this application. However, growing environmental, occupational health, and economic concerns have driven research toward sustainable alternatives. This paper reviews the performance, mechanisms, and recent advancements of vegetable oil-based cutting fluids in various machining operations. Drawing upon current literature, this review examines the lubricity, cooling capacity, and tribological behaviors of biological oils when applied to both ferrous and non-ferrous metals. Advanced application strategies, including Minimum Quantity Lubrication (MQL) and nano-fluid formulations, are also critically evaluated.

Keywords: Sustainable Machining, Vegetable Oil, Metalworking Fluids, Minimum Quantity Lubrication.

الملخص:
يعتمد قطاع التصنيع بشكل كبير على سوائل تشغيل المعادن لتبريد وتزييت منطقة القطع، مما يحسن عمر الأدوات وجودة السطح. تاريخيًا، هيمنت الزيوت المعدنية المشتقة من البترول على هذا الاستخدام. إلا أن تزايد المخاوف البيئية والصحية المهنية والاقتصادية دفع البحث نحو بدائل مستدامة. تستعرض هذه الورقة أداء وآليات وأحدث التطورات في سوائل القطع المشتقة من الزيوت النباتية في عمليات التشغيل المختلفة. بالاستناد إلى الدراسات المنشورة، تتناول هذه المراجعة خصائص التزييت والتبريد والسلوك الاحتكاكي للزيوت البيولوجية عند استخدامها على المعادن الحديدية وغير الحديدية. كما تقيم استراتيجيات التطبيق المتقدمة، بما في ذلك التزييت بكمية قليلة (MQL) وتركيبات السوائل النانوية، تقييمًا نقديًا.

الكلمات المفتاحية: التشغيل الآلي المستدام، الزيوت النباتية، سوائل تشغيل المعادن، الحد الأدنى من مواد التزييت.

Introduction:

Machining processes, such as turning, milling, and drilling, generate significant heat and friction at the tool-workpiece interface. To mitigate these effects, metalworking fluids (MWFs) are universally employed [1-13]. Traditionally, petroleum-based mineral oils and synthetic fluids have been the primary choice due to their availability and established performance [14-19]. However, these conventional fluids pose severe environmental and occupational health hazards, including skin diseases, respiratory issues from mist generation, and complex disposal protocols [7,19].

The push for "green" and sustainable machining has positioned vegetable oil-based cutting fluids as highly viable alternatives [10,20,21]. Vegetable oils are renewable, biodegradable, and possess excellent inherent lubricity due to their molecular structure [22-24]. This review synthesizes recent experimental data to evaluate the efficiency of vegetable oils (both in straight biological forms and as formulated emulsions) across different machining parameters and workpiece materials.

Properties and Mechanisms of Vegetable Oils as MWFs:

Vegetable oils are primarily composed of triglycerides, which contain long-chain fatty acids. This specific chemical structure provides a dense, strong, and polar lubricating film that firmly attaches to metallic surfaces, significantly reducing friction at the cutting zone [18].

Advantages:

- **High Flash Point:** Vegetable oils typically have higher flash points than mineral oils, reducing fire hazards during high-speed machining [3].
- **High Viscosity Index:** They maintain their viscosity across a wider temperature range, ensuring consistent lubrication [15].
- **Biodegradability:** They offer superior environmental compatibility and simpler disposal processes compared to petroleum fluids [24].

Limitations:

Despite their advantages, raw vegetable oils face challenges such as poor thermal and oxidative stability. High temperatures at the tool-chip interface can cause the oil to oxidize rapidly, reducing its shelf life and effectiveness [5]. Researchers have attempted to mitigate this through chemical modification and the addition of extreme pressure (EP) additives [12, 16].

Performance Evaluation in Machining Operations:

The substitution of mineral oils with vegetable oils requires rigorous experimental validation across different cutting processes to assess standard machinability criteria, such as tool wear ($VT^n=C$, where V is cutting speed, T is tool life, and n,C are constants) and surface roughness (R_a).

In-Depth Analysis of Turning Operations:

Turning is arguably the most fundamental and widely researched machining operation for evaluating the tribological efficacy of new metalworking fluids. The continuous nature of the tool-workpiece engagement in cylindrical turning provides a stable environment to measure the three primary indicators of machinability: cutting forces, tool wear progression, and surface roughness.

Mechanisms of Cutting Forces:

During cylindrical turning, the mechanical energy required to shear the workpiece material is converted almost entirely into heat. The resultant cutting force (F_R) acting on the single-point cutting tool can be resolved into three mutually perpendicular components: the main cutting force (F_c), the feed force (F_f), and the radial or thrust force (F_r). This relationship is mathematically expressed as:

$$F_R = \sqrt{F_c^2 + F_f^2 + F_r^2}$$

The application of cutting fluids aims to reduce these forces by minimizing the coefficient of friction (μ) at the secondary shear zone (tool-chip interface). Ojolo et al. [6] conducted experimental determinations of cutting forces during the cylindrical turning of mild steel using various straight biological oils. Their findings indicated that biological oils, due to their highly polar long-chain fatty acids, form a resilient, tightly packed molecular boundary film on the metallic surfaces.

This boundary lubrication significantly lowered the main cutting force (F_c) when compared to dry machining, directly translating to lower power consumption and reduced mechanical stress on the machine tool spindle [6].

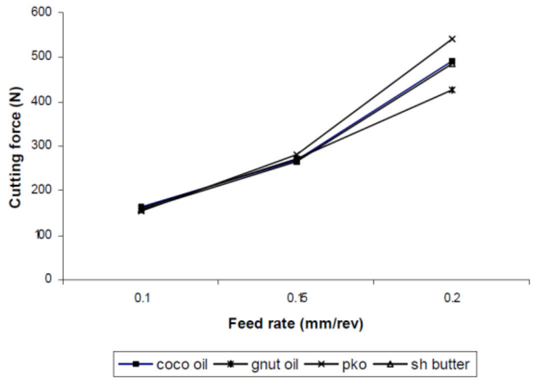

Figure (1): Variation of cutting force with feed rate on mild steel at 2mm depth of cut using the four Lubricants [6].

Tool Flank Wear Progression and Thermal Managing:

Tool wear, particularly flank wear (*VB*) occurring on the clearance face of the tool, dictates the tool effective lifespan and the precision of the machined component. High temperatures at the primary and secondary shear zones accelerate adhesive and diffusive wear mechanisms.

Vegetable oils exhibit remarkable thermal stability when applied correctly, mitigating these wear mechanisms. Khan et al. [1] investigated the turning of AISI 9310 alloy steel using vegetable oil-based cutting fluids applied via Minimum Quantity Lubrication (MQL). The study demonstrated that the superior penetration capability of the vegetable oil mist under high pressure allowed the fluid to reach the microscopic capillary network at the tool-chip interface. Consequently, the maximum cutting temperature was drastically reduced, which directly delayed the onset of severe flank wear and prevented premature catastrophic tool failure compared to standard flood cooling [1].

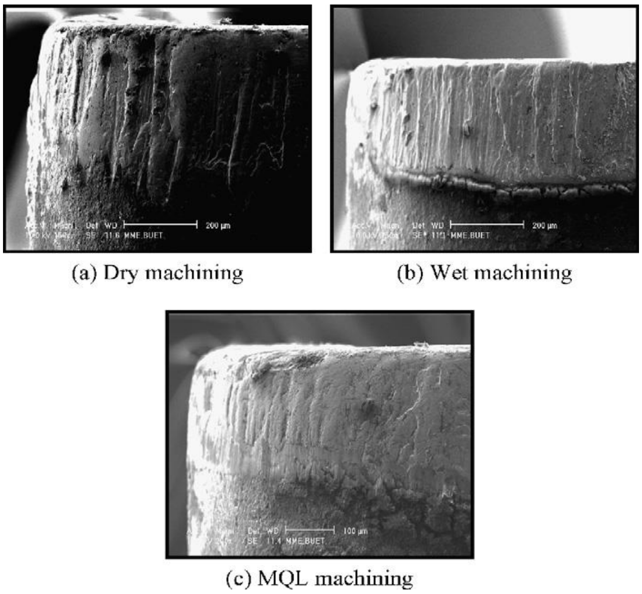

Figure (2): SEM views of principal flank wear of the worn out insert after machining 43 min under dry, wet and MQL conditions [1].

Furthermore, Sodavadia and Makwana [14] explored the limits of vegetable oils by modifying them into nano-cutting fluids. In their experimental investigation turning AISI 304 austenitic stainless steel (a material notorious for its poor machinability and high work-hardening rate) they utilized a coconut oil-based nanofluid. The inclusion of nanoparticles dramatically increased the thermal conductivity of the base coconut oil. This synergistic effect not only provided the excellent boundary lubrication inherent to vegetable oils but also removed heat from the cutting zone much more efficiently, resulting in a quantifiable reduction in flank wear width (*VB*) [14].

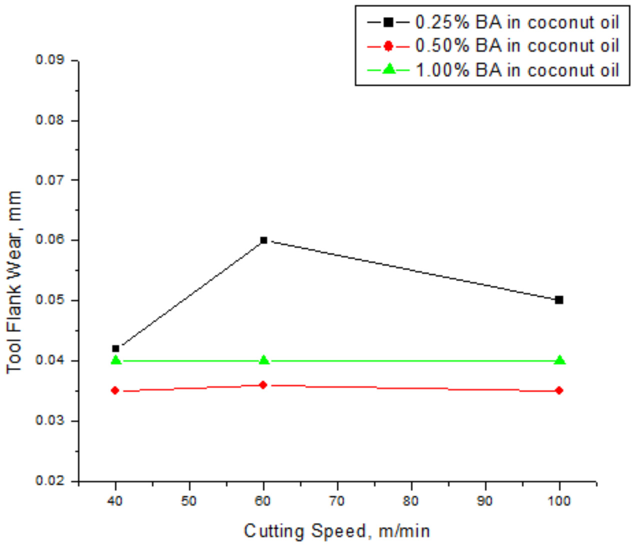

Figure (3): Variation of Tool flank wear with Cutting speed [14].

Surface Roughness and Dimensional Deviations:

Surface integrity is a critical quality metric in manufacturing. Theoretically, the ideal surface roughness (R_a) in turning is purely a geometric function of the feed rate (f) and the tool nose radius (R), approximated by the equation:

$$R_a \approx \frac{f^2}{8R}$$

However, in practice, factors such as Built-Up Edge (BUE) formation, tool vibration, and tearing of the workpiece material cause the actual R_a to deviate significantly from the theoretical value. The lubricity of vegetable oils plays a crucial role in preventing BUE. By reducing the temperature and friction at the tool tip, vegetable oil-based fluids prevent the localized welding of chip material to the tool face.

Both Khan et al. [1] and Sodavadia and Makwana [14] reported measurable improvements in surface finish when using formulated vegetable oils. The high viscosity index of the vegetable and coconut base oils ensured that the lubricating film remained intact even at elevated cutting speeds, suppressing tool chatter and resulting in a smoother surface topography with tighter dimensional accuracy.

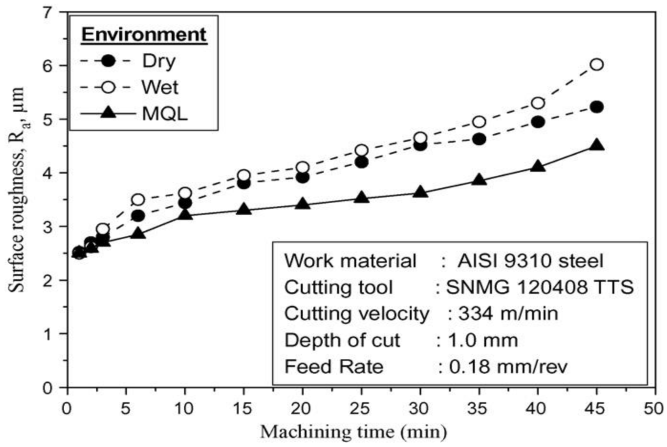

Figure (4): Variation in surface roughness with progress of turning steel by SNMG insert under different cooling conditions at cutting velocity 334m/min and feed rate 0.18mm/rev [1].

Tribological Dynamics in Milling and Drilling Operations:

While turning represents a continuous cutting process, milling and drilling introduce complex, distinct tribological challenges due to their interrupted nature and confined cutting geometries. Evaluating vegetable oil-based metalworking fluids (MWFs) in these operations is critical for validating their versatility across the manufacturing spectrum.

Intermittent Cutting Dynamics and Chip Formation in Milling

Milling is characterized by intermittent cutting, where the cutting teeth cyclically enter and exit the workpiece. This cyclic engagement subjects the cutting edges to severe mechanical impacts and rapid thermal fluctuations, which can lead to thermal fatigue, micro-chipping, and ultimately, catastrophic tool failure.

The application of a cutting fluid in milling must simultaneously provide extreme pressure (EP) lubrication to cushion mechanical shocks and adequate cooling to stabilize thermal cycling. Adam et al. [20] conducted a comprehensive study on surface roughness and chip formation during the end milling of mild steel using vegetable-based oils as lubricants. Their research highlighted the exceptional boundary lubrication properties of vegetable oils under interrupted cutting conditions.

Furthermore, chip formation mechanics in milling are heavily influenced by the frictional conditions at the tool-chip interface. High friction leads to tightly curled, continuous chips that can tangle around the spindle, scoring the newly machined surface. Adam et al. [20] observed that the strong adsorption of the polar fatty acid molecules in vegetable oils formed a robust lubricating film that reduced the coefficient of friction. This optimal lubricity promoted favorable chip curl and efficient chip evacuation away from the cutting zone, directly contributing to a superior surface finish and minimizing dimensional deviations on the mild steel workpieces [20].

Machining and Frictional Heat in Drilling:

Drilling is widely considered one of the most severe machining operations due to its enclosed cutting geometry. Unlike turning or milling, where heat can dissipate into the surrounding environment, drilling traps heat at the bottom of the hole. Furthermore, the cutting fluid must travel down the flutes against the upward flow of exiting chips to reach the critical cutting zones: the chisel edge and the main cutting lips.

The mechanical resistance in drilling is primarily measured by the thrust force (F_z) and the drilling torque (M_z). High friction between the drill margins and the hole wall, combined with the extreme pressure at the chisel edge, necessitates a lubricant with exceptional load-carrying capacity.

Ozcelik et al. [11] extensively investigated the effects of formulated vegetable-based cutting fluids on tool wear during the drilling of AISI 1040 steel. Pure vegetable oils often lack the oxidative stability required for the extreme localized temperatures found in deep-hole drilling. Therefore, the researchers utilized formulated vegetable fluids containing specific additives to enhance their high-temperature stability and extreme pressure capabilities.

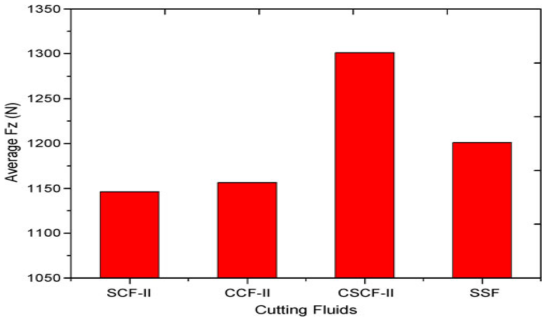

Figure (5): Average thrust force when drilling AISI 304 using cutting fluids (spindle speed of 750 rpm and feed rate of 0.1 mm/rev) [11].

Their experimental results demonstrated a significant reduction in both thrust force and torque compared to dry drilling and conventional commercial fluids [11]. The formulated vegetable oils effectively penetrated the severe contact zones, maintaining a persistent hydrodynamic and boundary film. By minimizing the adhesive wear at the cutting lips and reducing the frictional heat generated at the drill margins, the vegetable-based fluids substantially prolonged drill life and maintained tighter hole tolerances [11]. The capacity of these bio-lubricants to mitigate the intense tribological stresses of drilling underscores their viability as high-performance alternatives to petroleum-based fluids.

Plain Contact Mechanics: Tapping and Grinding:

While turning, milling, and drilling cover the bulk of general machining, operations like tapping and grinding represent the extreme ends of the tribological spectrum. Tapping is characterized by exceptionally high friction at low cutting speeds, whereas grinding involves massive thermal energy generation at high speeds. Evaluating vegetable oil-based fluids in these domains provides a comprehensive picture of their boundary lubrication and cooling capacities.

Boundary Lubrication and Tapping Torque Efficiency:

Tapping is an internal threading process notorious for its high failure rate. The operation features extensive rubbing and a continuous, multi-point engagement between the tap and the workpiece. Because tapping occurs at relatively low cutting speeds, hydrodynamic lubrication cannot be established. Consequently, the tool-chip and tool-workpiece interfaces operate almost entirely under the boundary lubrication regime, making the chemical properties of the metalworking fluid (MWF) the primary determinant of success.

To empirically measure the lubricity of MWFs, the tapping torque test is widely recognized as the industry standard. The mechanical efficiency of a cutting fluid in this context is inversely proportional to the torque required to cut the thread. The efficiency (E) is often calculated relative to a baseline reference fluid using the relationship:

$$E = \left(\frac{T_{ref}}{T_{test}}\right) \times 100$$

where T_{ref} is the average torque of the reference fluid and T_{test} is the average torque of the candidate fluid.

Clarens et al. [22] conducted an extensive experimental comparison of vegetable and petroleum base oils using the tapping torque test on 1018 steel. Their research highlighted the fundamental chemical advantage of vegetable oils. The triglyceride structure of vegetable oils contains polar ester groups that act as a "head," which electrochemically bonds to the metallic surface, while the long hydrocarbon chains act as a "tail," pointing outward to create a dense, self-assembled monolayer.

This resilient molecular carpet provides superior slip and prevents metal-to-metal contact even under extreme pressures. Clarens et al. demonstrated that vegetable oils, both in their straight form and as formulated emulsions, consistently yielded lower tapping torque values compared to traditional petroleum base stocks [22]. This reduction in torque directly correlates to less tool wear, reduced risk of tap breakage, and improved thread surface finish.

Specific Energy and Thermal Managing in Grinding:

In stark contrast to tapping, grinding relies on the abrasive action of countless randomly oriented micro-cutting edges (abrasive grains). A defining characteristic of grinding is the "size effect," which dictates that as the undeformed chip thickness decreases, the specific energy (u) required to remove a unit volume of material increases dramatically.

A significant portion of this specific energy is converted into heat, which is directed into the workpiece. If the fluid cannot cool the contact zone effectively, the workpiece will suffer from severe thermal damage, including metallurgical burn, phase transformations, and the induction of tensile residual stresses. Therefore, an effective grinding fluid must balance exceptional lubricity to reduce friction-generated heat with high cooling capacity to extract the remaining thermal energy.

Alves and Oliveira [19] addressed this complex challenge by developing new cutting fluids specifically formulated for the grinding process. Recognizing that straight vegetable oils have lower thermal conductivity than water-based fluids, their research focused on creating vegetable oil-in-water emulsions. These formulations aimed to adjust mechanical performance while drastically lowering environmental impact.

Their findings indicated that optimizing the concentration and droplet size of the vegetable oil emulsion allowed the fluid to penetrate the critical grinding contact arc. The vegetable oil phase provided the necessary lubricity to reduce the specific grinding energy (u), while the water phase delivered the essential bulk cooling required to prevent thermal damage [19]. This delicate balance confirms that, with proper formulation, vegetable-based fluids can successfully manage the severe thermomechanical demands of grinding operations.

Advanced Application Techniques and Delivery Mechanisms:

While the inherent chemical properties of vegetable oils offer excellent boundary lubrication, their higher kinematic viscosity and lower thermal conductivity compared to water-based synthetic fluids present challenges in high-speed machining. Furthermore, the higher base cost of biological oils necessitates highly efficient delivery methods. To address these physical and economic constraints, researchers have successfully integrated vegetable oils with advanced application technologies, primarily Minimum Quantity Lubrication (MQL) and nanotechnology.

Fluid Mechanics of Minimum Quantity Lubrication (MQL):

Minimum Quantity Lubrication (MQL), often referred to as Near-Dry Machining (NDM), is a technique that radically reduces fluid consumption. Instead of flooding the cutting zone with liters of fluid per minute, MQL delivers a precise, minute amount of lubricant (typically ranging from 10 to 100 mL/h) atomized in a high-velocity compressed air stream.

The efficacy of MQL relies heavily on the fluid mechanics of atomization and the momentum of the generated micro-droplets. When compressed air shears the high-viscosity vegetable oil, it creates an aerosol mist. The high-pressure air acts as a carrier, providing the kinetic energy necessary for the micro-droplets to penetrate the dense thermal boundary layer surrounding the high-speed rotating workpiece and tool.

Once the droplets reach the tool-chip interface, the fluid's ability to penetrate the microscopic asperities is governed by capillary action. The capillary pressure (p) drawing the fluid into these interstitial voids can be modeled by the Young-Laplace equation:

$$p = \frac{2\gamma cos\theta}{r}$$

where γ is the surface tension of the vegetable oil, θ is the contact angle (representing wettability), and r is the effective radius of the capillary gap. Vegetable oils, possessing high polarity, exhibit excellent wettability (low θ) on metallic surfaces, maximizing this capillary pressure.

Khan et al. [1] empirically demonstrated the synergistic effect of combining MQL with vegetable oil during the turning of AISI 9310 alloy steel. Their results showed that the vegetable oil mist, delivered via MQL, penetrated the cutting zone much more effectively than conventional flood cooling. The compressed air provided substantial convective cooling, while the atomized vegetable oil droplets formed a highly resilient, low-friction tribofilm. This combination significantly lowered the cutting temperature, reduced the coefficient of friction, and ultimately extended tool life while utilizing a fraction of the fluid volume required by flood systems [1].

Heat Transfer and Tribological Enhancements in Nano-Cutting Fluids:

A primary limitation of straight vegetable oils is their relatively low thermal conductivity (k), which restricts their ability to rapidly dissipate intense localized heat generated during operations like drilling or grinding. To overcome this thermal barrier, modern research has focused on synthesizing nano-cutting fluids by suspending highly thermally conductive nanoparticles (e.g., Al_2O_3, C_uO, carbon nanotubes) within the vegetable oil base.

The addition of nanoparticles alters both the thermophysical and tribological properties of the base fluid. The enhanced effective thermal conductivity of the nanofluid (k_{nf}) can be approximated using established effective medium theories. such as the Maxwell model for spherical particles:

$$K_{nf} = K_f \left[\frac{K_p + 2K_f - 2\emptyset(K_f - K_p)}{K_p + 2K_f + \emptyset(K_f - K_p)} \right]$$

where k_f and k_p are the thermal conductivities of the base fluid and the nanoparticles, respectively, and Φ is the volumetric particle concentration.

Settu et al. [9] reviewed the application of vegetable oil-based nano-cutting fluids, emphasizing that the inclusion of nanoparticles transforms the lubrication mechanism. Beyond just increasing thermal conductivity, the solid nanoparticles act as physical spacers between the tool and the workpiece. Depending on their morphology, these particles provide a "rolling effect" (converting sliding friction to rolling friction), a "mending effect" (filling in surface micro-cracks), and a "polishing effect" (smoothing surface asperities).

This multi-faceted enhancement was practically validated by Sodavadia and Makwana [14] in their experimental investigation of coconut oil-based nanofluids. When turning AISI 304 austenitic stainless steel, the addition of nanoparticles to the coconut oil drastically improved heat extraction from the shear zones. The resulting lower operating temperatures prevented the severe work-hardening typical of AISI 304, thereby reducing adhesive wear on the cutting tool and lowering the total machining forces [14]. This proves that nano-formulations can elevate the cooling capacity of vegetable oils to match or exceed that of water-based synthetics while retaining their superior lubricity.

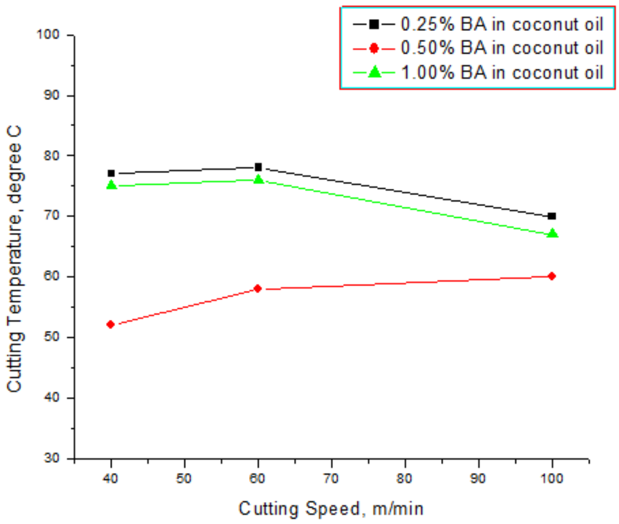

Figure (6): Variation of Cutting temperature with Cutting speed [14].

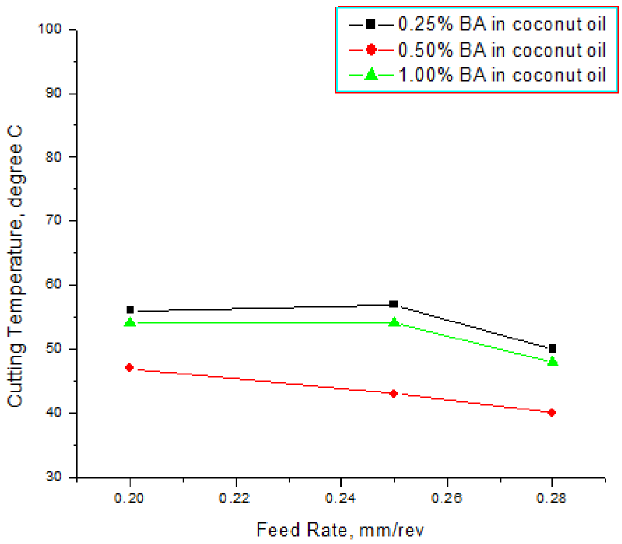

Figure (7): Variation of Cutting temperature with Feed Rate [14].

Comparative Analysis and Formulation of Organic Cutting Fluids:

To justify the widespread industrial transition from conventional petroleum-based fluids to sustainable alternatives, a rigorous comparative analysis of their thermophysical, tribological, and ecological properties is essential. Furthermore, understanding the chemical formulation processes required to overcome the inherent limitations of raw vegetable oils is critical for their practical application.

Comparative Tribological and Environmental Profiling:

Metalworking fluids are broadly categorized into three fundamental base stocks: mineral (petroleum-derived), synthetic (chemically synthesized polymers), and biological (vegetable or animal-derived). Papreja and Grewal [24] conducted a comprehensive comparative analysis of these eco-friendly vegetable, petroleum, and synthetic oil-based cutting fluids, evaluating their performance across standard machinability metrics.

- **Lubricity and Boundary Film Formation:** Vegetable oils exhibit vastly superior lubricity compared to mineral oils. As highlighted by Koushik et al. [3] and Chandrakar and Suhane [18], the triglyceride structure of vegetable oils provides long, polar fatty acid chains that strongly adhere to metallic surfaces. This creates a highly durable, closely packed boundary lubricating film that drastically reduces the coefficient of friction (μ) at the tool-chip interface. Mineral oils, being non-polar hydrocarbons, lack this inherent electrochemical affinity and rely heavily on the addition of extreme pressure (EP) additives to prevent metal-to-metal contact [24].
- **Cooling Capacity and Thermal Stability:** Synthetic fluids, particularly water-soluble synthetics and semi-synthetics, possess the highest cooling capacity due to the high specific heat of water. While straight vegetable oils have lower thermal conductivity than water-based fluids, their high viscosity index ensures that they maintain a stable lubricating film even at elevated temperatures. However, Koushik et al. [3] note that the primary drawback of raw vegetable oils is their poor oxidative and thermal stability. At high cutting temperatures, the unsaturated double bonds in the fatty acid chains are highly susceptible to auto-oxidation.

This rapid oxidation leads to polymerization, increased viscosity, and the formation of gummy residues on machine tools, severely limiting the shelf life and operational longevity of raw biological fluids [3, 18].

Chemical Modification and Fluid Formulation:

To harness the exceptional lubricity and biodegradability of vegetable oils while mitigating their oxidative instability and higher pour points, raw botanical extracts must undergo strategic chemical modification and formulation.

Rogoś and Urbański [15] thoroughly detailed the methods of preparation and the optimal use of cutting fluids based on organic components. They emphasized that transforming a raw vegetable oil into a high-performance metalworking fluid involves a multi-stage chemical engineering process.

Chemical Modification:

To address the oxidative degradation outlined in the equations above, the reactive double bonds within the unsaturated fatty acids must be stabilized. This is commonly achieved through chemical processes such as epoxidation or transesterification [15]. Epoxidation introduces an oxygen atom into the double bond, creating a more stable oxirane ring, which significantly enhances the oil's resistance to thermal breakdown and oxidation without compromising its biodegradability. Transesterification alters the molecular weight and structure, improving the fluid's cold flow properties (lowering the pour point) and ensuring consistent viscosity across varying operational temperatures.

Emulsification and Additive Packages:

For operations demanding high cooling rates, such as high-speed milling or grinding, straight modified oils are often formulated into oil-in-water (O/W) emulsions. Rogoś and Urbański [15] highlight the necessity of formulating stable emulsions using non-ionic or anionic surfactants. These emulsifiers reduce the interfacial tension between the oil and water phases, allowing the modified vegetable oil to disperse into micro-droplets within the water matrix.

Furthermore, a complete organic formulation requires a carefully balanced additive package:

- **Anti-oxidants:** To chemically intercept the free radicals and halt the propagation phase of auto-oxidation.
- **Corrosion Inhibitors:** To protect both the ferrous workpiece and the machine tool components from the water phase of the emulsion.
- **Biocides:** While the biodegradability of vegetable oils is an environmental asset, it makes the fluid susceptible to microbial and fungal degradation in the machine sump. Environmentally acceptable biocides must be integrated to prevent biological fouling and maintain pH stability [15].

By synthesizing these chemical modifications with advanced additive technologies, the inherent weaknesses of biological oils are neutralized, yielding a formulated MWF that offers the optimal balance of supreme lubricity, adequate cooling, extended fluid life, and exceptional environmental compatibility. To quantify the benefits of transitioning to sustainable machining, it is crucial to compare vegetable oils directly with conventional fluids.

Table (1): General Comparison of Metalworking Fluid Base Oils [3, 18, 24]

Property	Mineral Oil	Synthetic Oil	Vegetable Oil
Source	Petroleum (Non-renewable)	Chemical Synthesis	Plant-based (Renewable)
Lubricity	Moderate	Good	Excellent
Cooling Capacity	Good	Excellent	Moderate
Oxidation Stability	Good	Excellent	Poor to Moderate
Biodegradability	Low	Moderate	High (approx. 90-98%)
Toxicity / Health Risk	High	Moderate	Very Low

Table (2): Summary of Selected Experimental Studies on Vegetable Oil-Based MWFs

Reference	Process	Workpiece Material	Lubricant Type	Key Findings
Khan et al. [1]	Turning	AISI 9310 Steel	Vegetable Oil (MQL)	Reduced cutting temperature; improved surface finish over dry/flood.
Ozcelik et al. [11]	Drilling	AISI 1040 Steel	Formulated Veg. Oils	Significant reduction in thrust force and drill wear.
Clarens et al. [17]	Tapping	1018 Steel	Various Veg. Oils	Lower tapping torque compared to petroleum base stocks.
Sodavadia et al. [14]	Turning	AISI 304 Stainless	Coconut Oil + Nanoparticles	Enhanced thermal conductivity; reduced flank wear.
Kolawole et al. [2]	Machining	Mild Steel	Vegetable Emulsions	Comparable performance to commercial mineral soluble oils.

Environmental and Occupational Health Impacts

The primary catalyst for the paradigm shift from petroleum-based metalworking fluids (MWFs) to vegetable-based alternatives is the profound need to mitigate severe occupational health hazards and environmental degradation. The total lifecycle of an MWF—from its application on the shop floor to its eventual disposal—must be evaluated through the lens of green manufacturing principles.

Mist Generation and Respiratory Health Mechanics

During high-speed machining operations, the centrifugal forces exerted by rotating tools and workpieces, combined with the high-pressure delivery of the fluid, atomize the MWF into a fine aerosol mist. Prolonged inhalation of petroleum-based mineral oil mist is a well-documented occupational hazard, strongly correlated with respiratory disorders such as asthma, hypersensitivity pneumonitis, and various dermatological conditions.

The respirability of these mist droplets is primarily dictated by their aerodynamic diameter. Droplets smaller than 5 to 10 micrometers (μm) can bypass the upper respiratory tract's defense mechanisms and deposit deep within the alveolar region of the lungs. Raynor et al. [7] conducted a critical investigation into the mist generation characteristics of metalworking fluids formulated using vegetable oils.

Their research demonstrated that the distinct physiochemical properties of vegetable oils (specifically their higher molecular weight, varying surface tension, and complex polymer-like chain structures) fundamentally alter the fluid mechanics of droplet formation. When subjected to high shear forces, vegetable oil formulations tend to generate a mist with a larger mass median aerodynamic diameter compared to mineral oils under identical conditions [7].

The settling velocity (v_s) of these airborne droplets can be approximated by Stokes' Law:

$$v_s = \frac{2r^2 g(\rho_p - \rho_f)}{9\mu}$$

where r is the droplet radius, g is the acceleration due to gravity, ρ_p is the density of the droplet, ρ_f is the density of the air, and μ is the dynamic viscosity of the air. Because vegetable oil droplets are generally larger (r is squared in the numerator), their settling velocity is significantly higher. Consequently, vegetable-based mist precipitates out of the worker's breathing zone much faster than mineral oil mist, drastically reducing the inhalation exposure risk [7].

Ecological Biodegradability and Effluent Management:

From an environmental standpoint, the disposal of spent mineral oil emulsions presents a massive ecological and economic burden. They are highly toxic to aquatic life and require complex, energy-intensive chemical splitting and ultrafiltration before the water phase can be discharged.

Conversely, vegetable oils are inherently biodegradable. The ester linkages in their triglyceride structure are highly susceptible to enzymatic hydrolysis by natural environmental microorganisms. While mineral oils may take years to break down and often leave toxic heavy metal residues, properly formulated vegetable oils can achieve over 90% primary biodegradability within 21 days. This rapid biological assimilation ensures that accidental spills or effluent discharges pose a negligible threat to soil and aquatic ecosystems, significantly lowering industrial waste management costs.

Challenges and Future Scope:

Despite the overwhelming tribological and environmental advantages documented in recent literature, the universal replacement of mineral oils with vegetable-based fluids faces several technical and economic hurdles that define the current frontier of MWF research.

Oxidative Stability and Extreme Environment Degradation:

As highlighted by Selopal and Bhatia [13], the most significant technical limitation of raw vegetable oils remains their poor oxidative and thermal stability. The high temperatures generated at the tool-chip interface accelerate the auto-oxidation of the unsaturated fatty acid chains. This degradation leads to increased fluid viscosity, the formation of insoluble varnishes on machine tool components, and a rapid decline in lubricating efficacy. Future research must prioritize the development of advanced, eco-friendly antioxidant additive packages and the genetic modification of oilseed crops (e.g., high-oleic variants) specifically engineered to yield base oils with enhanced thermal resilience [13].

Machining of Non-Ferrous Metals:

While the performance of vegetable oils in ferrous metal machining is well established, their application in non-ferrous metals presents unique challenges. Lawal [23] reviewed the application of vegetable oil-based cutting fluids in machining non-ferrous alloys, such as aluminum, copper, and titanium. Certain organic acids present in biologically derived fluids can chemically react with sensitive non-ferrous metals, leading to surface staining, galvanic corrosion, or the formation of sticky metallic soaps that inhibit chip evacuation. Formulating fluids with specialized metal deactivators and boundary-film passivators specifically tailored for non-ferrous aerospace and automotive alloys remains a critical area for future investigation [23].

Conclusion:

The pursuit of sustainable, high-performance manufacturing has positioned vegetable oil-based metalworking fluids as the most practical successors to conventional petroleum-based mineral oils. This comprehensive review of current experimental literature determines that the unique triglyceride structure of vegetable oils provides superior boundary lubrication, significantly reducing cutting forces, lowering frictional heat generation, and enhancing surface integrity across a wide spectrum of machining operations, including turning, milling, drilling, tapping, and grinding.

To overcome the inherent thermal conductivity limitations of biological oils, advanced application techniques such as Minimum Quantity Lubrication (MQL) and the synthesis of nano-cutting fluids have proven highly effective. These technologies not only optimize the tribological performance of vegetable oils but also drastically reduce fluid consumption, aligning perfectly with near-dry and green machining philosophies.

Significantly, the transition to vegetable-based MWFs offers weighty occupational health and environmental benefits. By generating larger, less respirable mist droplets and providing exceptional biodegradability, these fluids safeguard operator health and eliminate the severe ecological liabilities associated with mineral oil disposal. While challenges regarding long-term oxidative stability, non-ferrous material compatibility, and initial acquisition costs remain, ongoing advancements in chemical formulation and additive technology are systematically dismantling these barriers. Ultimately, the integration of vegetable oil-based metalworking fluids represents a critical and necessary evolution toward ecologically responsible, economically viable, and technologically advanced manufacturing systems.

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