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VEGETABLE SEED OIL-BASED MACHINING FLUIDS: A REVIEW

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ABSTRACT

This review investigates the potential of vegetable seed oils as sustainable, biodegradable alternatives to conventional petroleum-based metalworking fluids (MWFs). The study synthesizes existing research on the formulation, performance and application of vegetable oil-based metal working fluids. This choice was motivated by severe environmental; health and economic problems associated with the use of mineral oils. The findings revealed that vegetable oils, due to their polar fatty acid structure, offer superior inherent lubricity, excellent biodegradability, and effective cooling. It consistently outperforms dry machining and often rivals mineral oils by significantly reducing surface roughness, cutting temperature, tool wear, and cutting forces across operations like turning, milling, and drilling. The review highlights the critical role of additives (such as EP agents, antioxidants) and advanced formulations, including nanofluids and chemically modified oils, in overcoming challenges such as poor oxidative stability. Furthermore, sustainable application methods including minimum quantity lubrication (MQL) are emphasized as key to minimizing fluid consumption. Despite promising results, the findings identify persistent challenges of thermal instability, microbial susceptibility, and formulation complexity and underscores a significant research gap: the unexplored potential of African Elemi seed oil as a base for MWFs. The study concludes that vegetable seed oil-based MWFs are viable, eco-friendly solutions for green manufacturing, with future success depending on the optimization of non-edible oils, advanced additive packages, and hybrid application techniques.

Keywords*: Vegetable seed Oil; Machining; Cutting Fluids; Minimum Quantity Lubrication; Biodegradable Lubricants.*

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1. INTRODUCTION

Metal working fluids (MWFs) are essential to modern manufacturing, serving critical functions in machining operations such as cooling, lubrication, chip evacuation, and corrosion prevention (Kumar *et al*., 2023). For decades, the industry has predominantly relied on petroleum-based mineral oils due to their effectiveness and economic availability. However, mounting evidence underscores the severe environmental, health, and economic liabilities associated with these conventional fluids. Their non-biodegradable nature contributes to persistent soil and water contamination, while occupational exposure poses significant risks to operators including dermatological, respiratory, and potential carcinogenic effects (Deshpande and Jyothi, 2022; Mbishida *et al*., 2018). Furthermore, the escalating costs of disposal and tightening environmental regulations are compelling the manufacturing sector to seek sustainable alternatives (Asif and Gandhi, 2021). Conventional cutting fluids are primarily petroleum-based mineral oil emulsions applied through flood lubrication systems. Their principal functions include cooling the cutting zone, reducing friction, facilitating chip evacuation, minimizing tool wear, and protecting both the machined surface and machine tool components from corrosion (Kumar *et al*., 2022).

Experimental studies demonstrate that the application of cutting fluids significantly stabilizes cutting forces and improves machining efficiency compared to dry machining (Gürbüz and Gönülaçar, 2022; Salur, *et al*., 2025). The importance of cutting fluids in machining operations is further emphasized by comparative studies between dry and lubricated machining (Mbishida *et al*., 2018). Investigation by Gariani *et al*., (2016) shows that dry machining often leads to rapid tool deterioration, unstable power consumption, and poor surface quality due to insufficient heat dissipation and increased adhesion at the tool chip interface. In contrast, fluid assisted machining results in lower tool temperatures, improved surface roughness, and enhanced dimensional accuracy. Studies involving steel machining reported catastrophic tool failure under dry conditions at higher cutting speeds, whereas cutting fluid application ensured stable machining and extended tool life (Gunjal and Patil, 2018; Liu, *et al* 2025; Jouini, *et al* 2026). Despite their technical effectiveness, conventional mineral oil-based cutting fluids pose significant environmental and occupational health concerns (Rassol *et al.* 2026; Katam *et al.* 2023; Luo, *et al.* 2024). These fluids exhibit poor biodegradability and often contain toxic additives such as sulfur, chlorine, and heavy metals. Prolonged exposure has been associated with skin irritation, respiratory ailments, and long-term health risks for machine operators (Nett, *et al.,* 2021; Levilly, *et al.,* 2024). Additionally, disposal and recycling of spent cutting fluids present serious environmental challenges, contributing to soil and water contamination. These drawbacks have intensified regulatory pressure on industries to reduce or replace mineral oil-based fluids (Gajrani and Sankar, 2017). In response, alternative lubrication strategies such as minimum quantity lubrication (MQL) have gained prominence in metal cutting operations (Salur, *et al.,* 2025; Katam, *et al.,* 2023). MQL significantly reduces cutting fluid consumption by delivering a fine mist of lubricant directly to the cutting zone, thereby minimizing environmental impact while retaining lubrication effectiveness (Jia *et al*., 2017). However, studies indicate that the success of MQL is highly dependent on the lubricating efficiency, thermal stability, and biodegradability of the cutting fluid used (Jouini, *et al.,* 2026; Khan, *et al.,* 2025). Conventional mineral oils often show limitations under MQL conditions due to poor environmental compatibility and instability at elevated temperatures (Popat *et al*., 2024).

Consequently, research efforts have increasingly focused on the development of environmentally friendly cutting fluids capable of meeting the severe thermal and tribological demands of machining operations. Vegetable seed oil-based cutting fluids offer superior lubricity due to their polar fatty acid chains, along with high viscosity indices and excellent biodegradability. Investigation reported reductions in cutting temperature, tool wear, cutting forces, and surface roughness when vegetable oil-based fluids are used instead of conventional mineral oils (Nerkar *et al*., 2022; González *et al*., 2018). Several scholars have done research on vegetable seeds oil for use as cutting fluid, though the data are scattered.

The aim of this study is to consolidate existing knowledge on vegetable seed oil-based metalworking fluids, focusing on their formulation, tribological performance, and environmental benefits, in order to evaluate their potential as sustainable alternatives to mineral oil-based cutting fluids. The objective of this review is to review and synthesize existing literature on vegetable seed oil-based metalworking fluids, focusing on their technical feasibility, environmental advantages, and machining performance improvements compared with conventional mineral oil-based and dry machining conditions. To evaluate the influence of formulation chemistry including chemically modified vegetable oils, nano-enhanced additives, and functional additives (such as emulsifiers, anti-wear agents, antioxidants, and corrosion inhibitors) on the tribological stability, thermal behavior, and machining effectiveness of bio-based cutting fluids. To investigate advanced lubrication strategies, particularly minimum quantity lubrication (MQL) and hybrid cooling systems, and assess the effectiveness of optimization techniques such as Design of Experiments (DoE), Taguchi methods, Response Surface Methodology (RSM), and Grey Relational Analysis (GRA) in improving machining performance while reducing cutting fluid consumption.

2.0 MATERIALS AND METHOD

The literatures reviewed in this study was sourced from reputable academic databases to ensure the inclusion of high quality, peer reviewed research. The primary databases consulted included Scopus, Web of Science, ScienceDirect (Elsevier), and Google Scholar. These databases were selected because they are high index journals in manufacturing engineering, tribology, materials science, and sustainable machining. A structured keyword search strategy was adopted. Core keywords and their combinations included “mineral oil-based cutting fluid” “vegetable oil-based cutting fluids”, “bio-based metalworking fluids”, “non-edible vegetable oils in machining”, “minimum quantity lubrication (MQL)”, “nanofluid cutting fluids”, “sustainable machining”, “green manufacturing”, and “metal cutting fluid performance”. Boolean operators (AND, OR) were used to refine searches and improve relevance.

The scope of the review focused on experimental, analytical and review studies that investigated the performance of vegetable seed oils both edible and non-edible as metal cutting fluids. Particular emphasis was placed on studies reporting machining performance indicators such as surface roughness, cutting temperature, tool wear, cutting force, chip morphology, and environmental sustainability. Research covering advanced lubrication strategies such as MQL, nanofluids, chemically modified oils, and hybrid cooling techniques was also included. Studies unrelated to machining or lacking measurable performance outcomes were excluded. In terms of publication timeframe, the review primarily covered literatures published between 2015 and 2026, reflecting recent developments in sustainable manufacturing and eco-friendly lubrication technologies. Lastly, this approach ensured that the reviewed literatures are current, relevant, and scientifically robust, providing a reliable foundation for analyzing the development and performance of vegetable seed oil-based metal cutting fluids.

3.0 RESULTS AND DISCUSSION

The findings obtained from relevant studies are discussed under the following heading, Cutting Fluids, Types, Classification, Properties, Application, Formulation and Development of Vegetable Oil-Based Cutting Fluids, Additives and Machining Performance of Vegetable Seed Oil Cutting Fluids are given below,

3.1 **Mechanisms of Metal Cutting Fluids**

Cutting fluids are used for improving the cutting condition and life of the tool. It is also referred to as Coolant or lubricant because it is used to reduce the heat generated during the metal working operation or in other words to cool the cutting tools. It mostly comes in liquid form but can be in gaseous form too (Kumar *et al.*, 2022). The primary role is to reduce friction between the cutting tool and the workpiece and at the tool chip interface. Effective lubrication minimizes cutting forces, reduces energy consumption, and prevents phenomena like built-up edge formation, directly contributing to improved surface finish and extended tool life (Gajrani and Sankar, 2017; Asif and Gandhi, 2021). Machining generates intense localized heat, which can thermally soften the tool, induce workpiece distortion, and accelerate tool wear mechanisms such as diffusion and plastic deformation. Cutting fluids absorbs and carry away this heat, maintaining dimensional accuracy and preserving the metallurgical integrity of both the tool and workpiece (Sharmin *et al.*, 2020). Cutting Fluids helps in flushing chips away from the cutting zone. Efficient chip evacuation prevents chip re-cutting, which can degrade surface finish, and reduces the risk of chip entanglement that could damage the tool or workpiece (Nizamuddin *et al.*, 2018). Cutting fluids provide a protective film on newly machined metal surfaces, shielding them from oxidation and environmental corrosion during and immediately after the machining process (John and Eng, 2015).

3.2 **Types of Cutting Fluids**

Cutting fluids are broadly categorized based on their composition, with each type offering a distinct balance of lubrication, cooling, and stability.

i. **Straight Oils (Neat Oils):** These are non-emulsifiable fluids used in their pure form, typically consisting of mineral, vegetable, or animal oils, often fortified with extreme pressure (EP) additives. They excel in lubrication for severe operations like broaching and gear cutting but offer poorer cooling and pose higher fire risks (Khosrovzadeh, 2022).

ii. **Water-Miscible Fluids:**

  a. **Soluble Oils (Emulsions):** The most common traditional type, formed by emulsifying mineral oil in water (typically 3-10% oil). They provide a good balance of cooling (from water) and lubrication (from oil) and are cost-effective for general-purpose machining (Roberto *et al.*, 2019).

  b. **Semi-Synthetic Fluids:** Micro-emulsions containing a lower proportion of mineral oil (less than 30%) along with synthetic surfactants and emulsifiers. They offer better cooling, stability, and visibility than soluble oils but can be more expensive (Gajrani *et al.*, 2017).

  c. **Synthetic Fluids:** Chemical solutions contain no petroleum oil. They are formulated from organic and inorganic compounds in water. Synthetics provide superior cooling, cleanliness, and biostability but often have lower lubricity and can be more corrosive (Deshpande and Jyothi, 2022).

iii. **Sustainable/Bio-based Fluids:** This emerging category is central to green manufacturing. It primarily includes vegetable oil-based fluids (e.g., from castor, coconut, neem, jatropha) and their enhanced derivatives, such as epoxidized oils for stability or nanofluids with dispersed nanoparticles (such as MWCNTs, Al_2O_3, MoS_2). Their defining characteristics are high biodegradability, renewability, excellent inherent lubricity, and low toxicity, making them environmentally responsible alternatives (Mbishida *et al*., 2018; Okokpujie *et al*., 2022).

3.3 **Classification of Cutting fluids:** Ejeh, (2015) classify cutting fluid as follows;

i. **Liquids:** There are generally three types of liquids: mineral, semi-synthetic, and synthetic. Water is a great conductor of heat but has drawbacks such as cutting fluid. It boils easily and promotes rusting of machine parts. Therefore, other ingredients which are necessary to create an optimal cutting fluid need to be added.

ii. **Pastes or Gels:** Cutting fluids may also take the form of paste, or gels, which are used for some applications, in particular, hand operations such as drilling and tapping. In sawing metal with a band saw, it is common to periodically run a stick of paste against the blade. This product is similar in form to lipstick or beeswax. It comes in a cardboard tube, which gets slowly consumed after application.

iii. **Aerosols (Mists):** Some cutting fluids are used in aerosol (mist) form (air with tiny droplets of liquid scattered throughout). The main problems with mists have been that they are unsuitable for the workers, who must breathe the surrounding mist tainted air, and these substances often don't even work well. Both problems come from the imprecise delivery that often puts the mist everywhere all the time, except the cutting interface where it is needed. However, a newer form of aerosol delivery, MQL (minimum quantity of lubricants), avoids both problems.

iv. **Air or other gases (e.g., nitrogen):** Ambient air, of course, was the original machining coolant. Compressed air, supplied through pipes and hoses from an air compressor and discharged from a nozzle aimed at the tool, is sometimes a useful coolant. The force of the decompressing air stream blows chips away, and the decompression itself has a slight degree of cooling ($pV= nRT$); (lowering the pressure lowers the temperature).

3.4 **Cutting Fluid Properties**

Cutting fluids play a critical role in metal machining operations by improving tool life, surface finish, dimensional accuracy, and overall process efficiency. The effectiveness of cutting fluid is determined by its physical, chemical, thermal, and environmental properties. A good cutting fluid should have the following properties:

i. Lubricating Property

Lubrication is one of the most critical properties of cutting fluids. It reduces friction at the tool chip interface and along the flank face of the cutting tool. Effective lubrication lowers cutting forces, minimizes tool wear, suppresses built-up edge formation, and improves surface finish of the machined component. The lubricating ability of a cutting fluid largely depends on its molecular structure and the presence of polar compounds capable of forming a strong adsorption film on metal surfaces. Fluids rich in fatty acids provide superior boundary lubrication, especially under high pressure and low speed machining conditions (Gajrani and Sankar, 2017).

ii. Cooling Properties

Cooling is another fundamental function of cutting fluids. During machining, excessive heat generation can lead to thermal softening of the tool, dimensional inaccuracies, and surface damage of the workpiece. A cutting fluid with good cooling capability effectively absorbs and transports heat away from the cutting zone. Water-based cutting fluids are particularly effective coolants due to their high specific heat capacity and thermal conductivity. Adequate cooling helps to stabilize the machining process, extend tool life, and maintains metallurgical integrity of the workpiece material Gupta *et al*., 2019; Li *et al*., 2017).

iii. Viscosity and Flow Characteristics

Viscosity significantly influences the performance of cutting fluids. It determines the fluid's ability to form a lubricating film and to flow into the cutting zone. Fluids with excessively high viscosity may impede heat dissipation and chip evacuation, while very low viscosity fluids may fail to maintain an effective lubricating layer. Therefore, cutting fluids are formulated to achieve an optimal viscosity that balances lubrication and cooling requirements under varying machining conditions (Okokpujie *et al*., 2022**).**

iv. Chemical Stability and Oxidation Resistance

Cutting fluids are subjected to elevated temperatures, pressures, and continuous exposure to air during machining. Chemical stability is essential to prevent degradation, sludge formation, and loss of functional performance. Oxidation resistance is particularly important, as oxidation leads to increased acidity, unpleasant odors, and reduced lubricating efficiency. The incorporation of additives such as antioxidants enhances the oxidative stability of cutting fluids, ensuring consistent performance over extended service periods (Puttaswamy and Ramachandra, 2018).

v. Corrosion Protection Properties

Corrosion protection is a vital property, especially for water-based cutting fluids. The presence of moisture can promote rust formation on machine components and workpieces if not adequately inhibited. Cutting fluids are therefore formulated with corrosion inhibitors that form protective films on metallic surfaces. Effective corrosion protection not only preserves machine integrity but also ensures high surface quality of machined parts and reduces post-machining finishing requirements (Roberto *et al*., 2019).

vi. Wettability and Penetration Ability

Wettability refers to the ability of cutting fluid to spread and adhere to metal surfaces. Fluids with low surface tension exhibit improved wetting characteristics, allowing them to penetrate effectively into the tool chip interface. Enhanced penetration ensures efficient lubrication and heat transfer at the cutting zone. Improved wettability is particularly beneficial in high-speed machining operations where fluid access to the cutting interface is challenging (Araújo *et al.*, 2017).

vii. Environmental and Health Properties

In recent years, increasing environmental regulations and occupational health concerns have emphasized the importance of environmentally considerate cutting fluids. Properties such as biodegradability, low toxicity, minimal skin irritation, and reduced mist formation are now critical selection criteria. Environmentally friendly cutting fluids help reduce disposal costs, environmental pollution, and health risks to machine operators, making sustainability an integral aspect of cutting fluid development (Gajrani *et al.*, 2017).

viii. Economic and Maintenance Considerations

From an industrial perspective, cutting fluids must also be economically viable and easy to maintain. Resistance to microbial growth, foaming control, ease of recycling, and long service life are desirable properties that reduce operational costs. Proper maintenance of cutting fluids ensures stable machining performance and minimizes downtime associated with fluid replacement and machine cleaning (Kazeem, *et al.*, 2022).

3.5 Cutting Fluids Application Methods

The method of fluid delivery is as crucial as the fluid type itself, significantly impacting consumption, efficiency, and environmental footprint.

i. **Flood Cooling:** The conventional method involving a high volume, continuous flow of fluid over the cutting zone. While effective for cooling and chip removal, it leads to massive fluid consumption (often 10,000+ liters annually per machine), high waste generation, and significant operator exposure to mist and splash (Gajrani and Sankar, 2017).

ii. **Minimum Quantity Lubrication (MQL) / Near-Dry Machining (NDM):** A sustainable application standard where a precise, tiny amount of fluid (typically 10-100 ml/h) is delivered as a fine aerosol or mist directly to the cutting interface using compressed air. MQL drastically reduces fluid usage (by over 90%), minimizes waste, and eliminates the need for costly chip-fluid separation, while often improving lubrication effectiveness due to better penetration (Pal *et al.*, 2018; Popat *et al.*, 2024).

iii. **Minimum Quantity Solid Lubrication (MQSL):** An advanced variant of Minimum Quantity Solid Lubrication (MQSL) where solid lubricant powders (e.g., graphite, MoS_2) are mixed with a small amount of vegetable oil and delivered as an aerosol. This method combines the ecological benefits of MQL with the superior high-temperature lubricating properties of solid lubricants, proving highly effective for machining superalloys like Inconel 718 (Marques *et al.*, 2019).

iv. **Cryogenic Cooling:** Cryogenic Cooling Involves applying cryogenic fluids like liquid nitrogen or CO_2 at the cutting zone. While not a lubricant, it provides extreme cooling, particularly beneficial for machining materials with poor thermal conductivity like titanium alloys. It is sometimes combined with MQL in hybrid approaches for simultaneous cooling and lubrication (Jamil *et al*., 2019).

3.6 **Vegetable Seed Oils as Base Fluids for Eco-Friendly Cutting Fluid**

The growing emphasis on sustainable and environmentally responsible manufacturing has driven significant research into alternative metalworking fluids. Traditional cutting fluids, often petroleum-based, pose environmental and health hazards due to poor biodegradability and toxic additives (Abutu *et al*., 2022). In response, vegetable seed oils have emerged as a promising, renewable, and eco-friendly base for cutting fluids. Vegetable oil-based metal cutting fluids are liquid agricultural products produced from plants, and they may be viable and highly attractive substitutes for petroleum-based oils because of their natural occurrence, high viscosity and high flash point, in addition to being renewable, biodegradable and non-toxic (Wara and Salihi, 2022). The above reasons make vegetable-based oils potential candidates for use in industry as metal cutting fluids. Research demonstrates a wide exploration of oil sources. Studies have successfully developed and characterized cutting fluids from palm kernel oil (Abutu *et al*., 2022), neem seed oil (Awode *et al*., 2022), soya beans (Ejeh, 2015), and rubber seed oil (Osayi *et al*., 2021). More novel sources were also being investigated, such as Balanites seed oil (Wara and Salihi, 2022) and Nigerian sweet orange seed oil (Yekini and Thomas, 2023), highlighting the vast potential of regionally available feedstocks. The primary advantage of these oils is their inherent lubricity, high viscosity index, and excellent biodegradability (Araújo *et al*., 2017).

3.6.1 **Formulation and Development of Vegetable Oil-Based Cutting Fluids**

Cutting fluids formulation is an important first step toward achieving the best fluid performance and the extension of fluid life by using correct fluid concentration efficiently. Historically, vegetable-based lubricants have not exhibited sufficient performance for industrial applications. There were several reasons for their inability. The first reason is that vegetable-based lubricants were mis-formulated. Early formulators in the vegetable-based lubricant market used the same chemistry that was used for mineral lubricants for vegetable-based oils. This approach was not effective because the characteristics of vegetable oils are vastly different from those of mineral oils. The type of additives used in the formulation of cutting fluids contribute to their properties and that these properties are usually mutually exclusive. The soluble oils (also referred to as emulsions, emulsifiable oils, or water-soluble oils) are generally comprised of 60–90% based oil, with emulsifiers and other additives (Wara and Salihi, 2022).

Concentrate is mixed with water to form the cutting fluids. When mixed, emulsifiers cause the oil to disperse in water forming a stable oil in water emulsion. They also cause the oils to cling to the workpiece during machining. The emulsifiers' particles refract light, giving the fluid a milky, opaque appearance. Sometimes, water miscible fluids may consist of up to 99% water, and then the quality of water used to dilute the concentrate becomes an important consideration in fluid preparation. This is because dissolved minerals and gases, organic matter, microorganisms, or combination of these impurities in water can lead to problems (Wara and Salihi, 2022). In a study of Anyanwu *et al*. (2023) and Awode *et al*. (2020), The formulation involves creating a stable oil-water emulsion using a high proportion of renewable base oil (80-100% of the oil phase) and additives (5-20%) to achieve lubrication, cooling, corrosion inhibition, and microbial stability comparable to conventional mineral oils. The study confirms that properly formulated bio-based fluids (especially Lard and Jatropha-based) can meet or exceed the performance of mineral oils in key machining parameters like surface finish, tool wear, and power consumption. Baba *et al*. (2018) did Formulation and Performance Assessment of Fixed Oils Based Cutting Fluids in Machining Operation. The base oil (Shea butter or Neem oil) was combined with emulsifier (washing soda), sulphur, and phenol in the ratio 80:10:5:5 at room temperature. The formulated concentrate was mixed with water in a 1:10 ratio (1 part cutting fluid to 10 parts water) to create the final cutting emulsion for machining.

3.6.2 **Additives Used in Vegetable Seed Oil Cutting Fluids**

Base oils alone, whether mineral or vegetable in origin, are often insufficient to meet the severe tribological, thermal, and chemical demands of modern machining operations. Consequently, additives are incorporated into lubricants and cutting fluids to enhance their functional performance, stability, and service life. In vegetable oil-based cutting fluids, additives are particularly critical because, although these oils exhibit excellent lubricity and biodegradability, they suffer from limitations such as poor oxidation stability, microbial growth, and inadequate extreme pressure resistance (Gajrani *et al*., 2017; Mbishida *et al*., 2018).

i. **Extreme Pressure (EP) Additives**

Extreme pressure additives are essential in machining operations involving high loads and temperatures, where boundary lubrication dominates. EP additives function by chemically reacting with the metal surface to form a protective tribofilm that prevents direct metal-to-metal contact. Sulfur- and chlorine-based compounds are commonly used EP additives in vegetable oil-based cutting fluids. For instance, sulfur has been successfully incorporated into coconut and soybean oil-based cutting fluids, resulting in significant reductions in cutting temperature and improved tool life during turning operations (Ejeh, 2015; Adedayo *et al*., 2022; Othman *et al*., 2022).

ii. **Anti-Wear (AW) Additives**

Anti-wear additives reduce progressive material loss from tools and workpiece surfaces under moderate load conditions. Unlike EP additives, AW additives operate without aggressive chemical reactions, instead forming thin, durable films that reduce friction and wear. Vegetable oil-based lubricants enhanced with AW additives have been reported to produce lower surface roughness and reduced flank wear, particularly in turning and milling applications (Yakubu and Bello, 2015; Kazeem *et al*., 2020).

iii. **Oxidation Inhibitors (Antioxidants)**

One of the major drawbacks of vegetable oils is their susceptibility to oxidative degradation due to high unsaturated fatty acid content. Oxidation leads to increased acidity, viscosity changes, and sludge formation, ultimately reducing lubricant effectiveness. Antioxidant additives delay oxidation by scavenging free radicals and decomposing hydroperoxides. The reviewed literature highlights that chemically modified oils (such as epoxidized jatropha and pongamia oils) and antioxidant-enhanced formulations exhibit improved oxidative and thermal stability, making them suitable for prolonged machining operations (Jeevan and Jayaram, 2018; Gajrani *et al.*, 2017).

iv. **Corrosion Inhibitors**

Corrosion inhibitors protect machine tools and workpieces from rust and chemical attack, especially in water-based emulsions and MQL systems. These additives function by forming a passive protective layer on metal surfaces or by neutralizing corrosive agents. Studies on mango kernel seed oil, watermelon seed oil, and African star seed oil formulations show that the inclusion of anti-corrosion additives significantly improves pH stability and reduces corrosion tendency compared to untreated vegetable oils (Kazeem, *et al.*, 2022; Ikumapayi *et al.*, n.d.).

v. **Biocides and Antimicrobial Additives**

Vegetable oil-based cutting fluids are prone to microbial contamination due to their organic nature. Biocides are therefore added to suppress bacterial and fungal growth, which can cause foul odor, pH reduction, and fluid degradation. Factorial design studies on watermelon and jatropha seed oil-based cutting fluids reveal that biocide concentration significantly influences acid value and viscosity, directly affecting fluid stability and service life (Kazeem, *et al.*, 2022).

vi. **Anti-Foaming Agents**

Foaming reduces lubrication efficiency, interferes with fluid delivery, and promotes oxidation. Anti-foaming additives, typically silicone-based, are used to suppress foam formation and enhance fluid flow characteristics. Experimental formulations documented in the reviewed studies show that anti-foam additives significantly influence viscosity and acid value, thereby improving the overall rheological performance of vegetable oil-based cutting fluids (Kazeem, *et al.*, 2022).

vii. **Nano-Additives in Lubricants**

Recent advancements highlight the use of nano-additives such as TiO_2, Al_2O_3, MWCNTs, CNTs, and graphite to enhance lubricant performance. Nano-additives improve thermal conductivity, load-carrying capacity, and tribological behavior through mechanisms such as rolling, mending, and protective film formation. Numerous studies reported substantial reductions in surface roughness (up to 50%), cutting force (30-35%), and tool wear when vegetable oil-based nanofluids are applied under MQL conditions (Nerkar *et al.*, 2022; Hegab *et al.*, 2018; Gupta *et al.*, 2019).

3.6.3 Machining Performance of Vegetable Seed Oil Cutting Fluids

Vegetable oil-based metalworking fluids (MWFs) have attracted significant research interest as sustainable alternatives to conventional mineral oil-based cutting fluids due to increasing environmental regulations, occupational health concerns, and the drive toward green manufacturing. Numerous experimental and review studies have evaluated their performance in metal cutting operations such as turning, drilling, milling, and grinding.

i. Surface Roughness and Surface Integrity

A dominant finding across reported studies is the consistent improvement in surface finish when vegetable oil-based MWFs are employed. Yakubu and Bello, (2015) demonstrated that neem oil reduced surface roughness by 39% compared to dry cutting and 22% compared to soluble oil during turning of Al-Mn alloy, attributed to enhanced boundary lubrication from polar fatty acid chains. Similarly, Puttaswamy and Ramachandra, (2018) reported that epoxidized Mahua oil produced significantly lower surface roughness than both mineral oil and neem oil during drilling of AISI 304 stainless steel, with feed rate contributing over 82% to surface roughness variation.

John *et al*., (2024) found that moringa oil and castor oil outperformed dry cutting in machining AISI 1040 steel, with moringa oil producing the smoothest surfaces due to reduced friction and cutting temperature. Comparable improvements were reported for coconut oil-based cutting fluids (Adedayo *et al*., 2022) and African star seed oil (Ikumapayi *et al*., n.d.), where surface roughness reductions of approximately 50% relative to mineral oil were achieved.

Putra *et al*. (2023) reported that optimized CNC turning parameters produced significantly lower surface roughness during the machining of Aluminum Alloy 6063, with spindle speed contributing approximately 59.71% and feed rate 29.80% to surface roughness variation, while depth of cut had a negligible effect, resulting in a minimum Ra of about 0.52 µm under high spindle speed and low feed rate conditions. Majak *et al*. (2020) reported that sunflower oil outperformed palm and coconut oils in the turning of AISI 304 stainless steel under minimum quantity lubrication, achieving lower surface roughness due to superior lubricity linked to fatty acid composition rather than viscosity alone. Studies show that feed rate, cutting speed, and depth of cut critically influence surface finish, with feed rate often being the most dominant factor (Ehibor and Aliemeke, 2021; Elmasrub *et al*., 2022; Kumar and Vashist, 2022; Vishal and Shaha, 2020). Low feed rates and moderate cutting speeds generally improve surface quality, while higher values enhance productivity but may reduce surface finish (Ghazi *et al*., 2019; Rizvi and Ali, 2021).

Depth of cut also affects surface roughness, partly through its impact on tool wear (Elmasrub *et al*., 2022; Do Thi Kim Lien *et al*., 2023). Collectively, these studies highlight that while cutting parameter optimization is fundamental to surface roughness control, the application of vegetable-oil-based lubricants can further enhance surface finish through improved boundary lubrication, underscoring the complementary roles of process parameters and sustainable cutting fluids in achieving superior surface quality. Chowdary *et al*. (2019) showed that surface finish in CNC turning of Al-6061 can be greatly improved through parameter optimization. Using a combined Taguchi-RSM-GA approach, they identified cutting speed, feed rate, depth of cut, and tool nose radius as key factors, with an optimal setting yielding minimum surface roughness. Validation experiments closely matched GA predictions, confirming the reliability of GA-based optimization for enhancing surface quality.

ii. Cutting Temperature and Cooling Performance

Vegetable oil based MWFs exhibit superior cooling performance compared to dry machining and often rival or exceed mineral oils. Gajrani *et al*., (2017) reported that bio-cutting fluids significantly lowered cutting temperature and friction coefficient under both flood cooling and minimum quantity cutting fluid (MQCF) conditions. Coconut oil-based cutting fluids reduced cutting temperature by 31% relative to petroleum-based fluids and by 60% compared to dry cutting during turning of AISI 1040 steel (Adedayo *et al*., 2022). These improvements are primarily linked to the high flash point, viscosity index, and strong affinity of vegetable oils to metal surfaces, which enable stable lubricating films at elevated temperatures (Gajrani and Sankar, 2017). Studies involving difficult-to-machine materials, such as Ti-6Al-4V and Inconel-800, further show that vegetable oil-based nanofluids under MQL conditions effectively mitigate heat generation, outperforming conventional wet machining in terms of thermal control (Hegab *et al*., 2018; Gupta *et al*., 2019). Adegbola *et al*. (2023) found that liquid soap provided the best temperature reduction (up to 72.84% on chips), but soluble oil gave the best surface finish (0.8 mm Ra) on mild steel when turning with HSS tools. Eze *et al*. (2022) showed that Gmelina oil (a vegetable oil) outperformed conventional soluble oil in minimum quantity lubrication (MQL) drilling, yielding the lowest cutting temperature and shortest drilling time, followed by soluble oil, Neem oil, and Castor oil. Dry machining consistently produced the highest temperatures and longest times.

iii. Tool Wear and Tool Life

Reduction in tool wear is another critical advantage reported in the literatures. Neem oil reduced flank wear by 72% compared to dry machining during turning of aluminum alloys (Yakubu and Bello, 2015). Jeevan and Jayaram, (2018) observed that epoxidized Pongamia oil resulted in the lowest flank wear when turning AA6061, significantly outperforming mineral oil. Similarly, castor oil-based cutting fluids produced lower tool wear than mineral oil when machining AISI 1020 steel (Ehibor *et al*., n.d.). Nanoparticle-enhanced vegetable oils further improve tool life by enhancing load-carrying capacity and thermal conductivity. Mustard oil based MWCNT nanofluids achieved the lowest surface roughness and tool wear in CNC turning operations (Nerkar *et al*., 2022), while CNT- and graphite-based vegetable oil nanofluids reduced tool wear by up to 44% in machining superalloys (Gupta *et al*., 2019). Bacak and Karabiyik, (2022) examined soy, sunflower, and canola oil water emulsions as eco-friendly cutting fluids for CNC turning of AISI 4140 steel and compares them with dry cutting and commercial fluid. At fixed cutting conditions, the best performance is obtained with pressurized spraying of a 7% canola oil 93% water mixture, which gives a tool wear of 0.13 mm, whereas dry cutting gives the worst results with tool wear ≈ 0.24 mm, confirming that properly applied vegetable oil emulsions can surpass conventional practice in both surface quality and tool life.

iv. Cutting Forces, Chip Formation, and Energy Efficiency

Vegetable oil based MWFs generally reduce cutting forces due to improved lubricity and reduced friction at the tool chip interface. Okokpujie *et al*., (2022) reported that TiO_2 and

MWCNT nanolubricants dispersed in copra oil reduced cutting forces by 5-6%, with feed rate and axial depth of cut being the most influential parameters. Chip morphology studies also reveal brighter, smoother chips under vegetable oil lubrication, indicating effective heat dissipation and stable cutting conditions (Kazeem *et al.*, 2020; Nizamuddin *et al.*, 2018). Energy efficiency benefits are also reported. Roberto *et al.*, (2019) showed that vegetable oil emulsions reduced power consumption during face milling of aluminum alloys compared to mineral oil, while maintaining lower tool temperatures and superior surface finish.

v. Environmental and Sustainability Performance

Beyond machining performance, vegetable oil–based MWFs offer clear environmental advantages. Gajrani *et al.*, (2017) quantified biodegradability values of 96.67% for bio-cutting fluids, compared to only 18.32% for mineral oil, highlighting their reduced ecological footprint. Reviews by Mbishida *et al.*, (2018), Asif and Gandhi, (2021), and Khosrovzadeh B, (2022) consistently conclude that vegetable oils align strongly with green manufacturing principles due to renewability, biodegradability, and reduced toxicity. However, challenges remain, particularly oxidative instability, poor low-temperature performance, and long-term storage stability. Many studies recommend chemical modification (e.g., epoxidation) and the use of eco-friendly additives or nanoparticles to overcome these limitations (Gajrani and Sankar, 2017; Deshpande and Jyothi, 2022).

3.6.4. Challenges in the Development of Vegetable Oil Cutting Fluids

Although vegetable oil-based cutting fluids offer significant environmental benefits, their large-scale industrial adoption is constrained by challenges such as poor oxidative and thermal stability, susceptibility to microbial degradation, formulation complexity, and reduced performance under severe machining conditions. Poor oxidative stability is a major limitation of vegetable oil-based cutting fluids, as their high unsaturated fatty acid content makes them prone to oxidation at elevated temperatures during turning operations. Oxidation increases viscosity, acid and sludge formation, and loss of lubricating performance, significantly reducing fluid service life and limiting long-term industrial application (Mbishida *et al.*, 2018). A key challenge for vegetable oil cutting fluids is thermal instability. The high temperatures generated during turning, especially at aggressive parameters, cause thermal degradation of the triglyceride molecules. This breakdown leads to a loss of lubricity and unpredictable performance. While these oils have high flash points (good for safety), they require chemical modification or thermal stabilizing additives to maintain effectiveness under sustained machining heat (Gajrani and Sankar, 2017). Microbial susceptibility poses a significant challenge, especially for water-emulsified vegetable oil fluids. The organic nature of oils provides a nutrient-rich environment that promotes bacterial and fungal growth. This leads to emulsion breakdown, foul odors, corrosion, and health hazards for operators. Consequently, microbial degradation shortens fluid life, increases maintenance, and hinders industrial adoption of these otherwise eco-friendly alternatives (Ejeh, 2015). Formulation complexity and additive compatibility present a major hurdle. Vegetable oils often lack the inherent stability and performance-enhancing properties of mineral oils, necessitating a tailored blend of emulsifiers, antioxidants, extreme pressure (EP) additives, and biocides. Selecting effective, compatible additives is critical, as improper formulations can result in phase separation, reduced lubricity, and chemical incompatibility, thereby increasing development costs and complicating production (Kazeem, *et al*., 2022). Performance under severe conditions is a noted limitation, as vegetable oil fluids may decline in effectiveness under high speeds, heavy feeds, or prolonged operations, where mineral oils still often outperform. The study indicates this underscores the need for further formulation optimization for extreme-pressure and high-temperature resilience. Additionally, economic and supply chain issues such as raw material variability, food-versus-fuel competition, and price instability challenge consistent large-scale production. A shift toward non-edible and waste-derived oils is highlighted as a promising path to improve feasibility and sustainability (Kumar *et al*., 2022; Susmitha *et al*., 2016).

3.6.5 **Recent Advances and Emerging Trends**

Research has evolved beyond evaluating straight vegetable oils toward sophisticated formulations and application techniques to overcome inherent limitations and enhance performance. The following trends represent the current boundary in this field. Vegetable oil-based nanofluids have emerged as a significant advancement in cutting fluid development, as the addition of nanoparticles such as CNTs, graphene, Al_2O_3, and MoS_2 greatly improves thermal conductivity and tribological performance. These nanofluids have been shown to substantially reduce cutting temperature, enhance surface finish, and extend tool life through improved heat transfer, rolling effects, and protective tribofilm formation (Sharmin *et al*., 2020; Nerkar *et al*., 2022; Yıldırım *et al*., 2019). Sahu *et al*. (2018) showed that a water-based MWCNT nanofluid significantly outperforms dry cutting and conventional fluids in turning Ti–6Al–4V. At optimized conditions, the nanofluid reduced tool wear, cutting forces, and surface roughness, with similar improvements confirmed at lower cutting speeds. The results demonstrate that nano-enhanced coolants effectively improve titanium alloy machinability by reducing cutting-zone temperature and friction.

Minimum Quantity Lubrication (MQL) has emerged as a sustainable alternative to flood cooling by reducing cutting fluid consumption by over 90% while maintaining effective lubrication. Hybrid approaches, such as solid lubricant assisted MQL and nanofluid–cryogenic cooling systems, further improve tool life, surface finish, and thermal control, especially in demanding machining conditions (Gunjal *et al*., 2021; Pal *et al*., 2018; Marques *et al*., 2017; Jamil *et al*., 2019; Putta, 2022). Chemical modification, such as epoxidation, improves the oxidative and thermal stability of vegetable oil-based cutting fluids, while systematic optimization of additive packages using Design of Experiment (DOE) methodologies (e.g., factorial design, Taguchi) to scientifically optimize complex additive blends containing emulsifiers, corrosion inhibitors, antioxidants, and biocides for maximum stability and performance (Jeevan and Jayaram, 2018; Puttaswamy and Ramachandra, 2018; Kazeem *et al*., 2020; Jeevan and Jayaram, 2018; Ejeh, 2015).

Recent research is focusing on non-edible and waste-derived vegetable oils, such as Mango Kernel, Watermelon Seed, African Star Seed, Neem, Karanja, and Jatropha, to avoid the food–fuel conflict and enhance sustainability, local availability, and supply chain security in cutting fluid development (Kazeem, *et al*., 2022; Ikumapayi *et al*., n.d.; Yakubu and Bello, 2015). Recent trends involve using advanced statistical and modeling tools, such as Grey Relational Analysis and Response Surface Methodology, for multi-response optimization of machining parameters and cutting fluid properties. These approaches enable simultaneous minimization of surface roughness, cutting temperature, and forces, and facilitate predictive modeling for accurate pre-process performance estimation (Kazeem, *et al*, 2022; Okokpujie *et al*., 2022; Gupta *et al*., 2019).

3.6.6 **Summary of Recent Biobased review**

John *et al*., (2024) investigated the effects of cutting speed and depth of cut on the surface roughness of AISI 1040 steel during turning operations under dry and vegetable oil-based (castor and moringa) lubrication. Results showed that higher cutting speed improved surface finish, while greater depth of cut increased roughness. Moringa oil performed best in reducing surface roughness and temperature, indicating that biodegradable vegetable oils are effective and eco-friendly alternatives to conventional cutting fluids. Okokpujie *et al*., (2022) conducted a comparative study on the performance of TiO_2 and MWCNT nano-lubricants against pure vegetable (copra) oil during the sustainable machining of Aluminum 8112 alloy. Using a Quadratic Central Composite Design, the study showed that both nano-lubricants significantly reduced cutting forces (by about 5–6%) and improved lubrication performance compared to pure vegetable oil, with TiO_2 performing slightly better due to its lower viscosity and superior thin-film formation. The authors concluded that dispersing nanoparticles in vegetable oils markedly enhances their rheological and machining performance, making nanofluids a promising option for sustainable machining applications.

Khosrovzadeh B, (2022) reviewed over 80 studies on vegetable oil-based machining fluids in green manufacturing to address the environmental and health risks of petroleum-based fluids. The review showed that vegetable oils consistently outperform mineral oils by significantly reducing cutting force, surface roughness, temperature, and tool wear across machining processes such as turning, milling, drilling, and grinding. It emphasized Minimum Quantity Lubrication (MQL) as the most efficient application method and highlighted nano-additives like MoS_2 and graphene as key enhancers of performance. The study concluded that vegetable oil-based, especially nano-enhanced, cutting fluids are technically viable and environmentally sustainable solutions for modern manufacturing. Jafarian, *et al*., (2022) evaluated the effect of a copper oxide (CuO) nanofluid enhanced with boric acid nanoparticles on high-speed turning of hardened AISI 4340 steels. The study tested a 1% CuO-based nanofluid with 0.25%, 0.5%, and 1.0% boric acid additions under a full factorial design against dry and conventional wet machining. Results showed that all nanofluids significantly reduced cutting force and improved surface finish, with the 0.5%

boric acid variant performing best reducing force by 31–34% and surface roughness by 58–59%, while minimizing tool wear. The authors concluded that optimal nanoparticle addition dramatically enhances lubrication and cooling, making nanofluid cutting fluids highly effective for sustainable high-speed machining of difficult-to-cut materials.

Sharmin *et al*., (2020) investigated the performance of carbon nanotube (CNT) enhanced vegetable oil-based nanofluids in turning operations. The study evaluated reductions in cutting temperature, improvements in surface finish, and tool life extension compared to conventional vegetable oils. Results showed that the CNT nanofluids reduced cutting temperature by 29%, improved surface finish by 34%, and significantly increased tool life. The performance enhancements were attributed to enhanced heat transfer, rolling (ball-bearing) effects, and the formation of protective tribofilms. The study concluded that nanofluid-enriched vegetable oils offer substantial tribological and thermal advantages, making them effective for sustainable machining.

3.7 **Study Gap**

It has been observed from the literatures reviewed that various plant seed oils have been used as vegetable oil-based cutting fluids such as neem seed, soya beans, cotton seeds, jatropha, palm oil, and ground nut oil but no particular research work has been conducted on the use of African Elemi seed oil (Canarium Schweinfurtii) as a vegetable oil-based cutting fluid. In a study of Kamtu *et al*., (2025) reported that African elemi seed oil performance as a neat lubricant in metal forming/forging is competitive with mineral oils, indicating good potential if adapted and stabilized for cutting-fluid applications. It shows low friction coefficients (around 0.09 – 0.084 in severe contact tests), which fall within the typical range reported for vegetable lubricants and are comparable to mineral oils (Kamtu *et al*., 2023; Mbishida *et al*., 2018; Kamtu *et al*., 2025). Ibeh *et al*. (2017) evaluated African elemi, melon, and African locust bean oils as alternative quenchants to mineral SAE 40 oil for heat treatment of medium-carbon steel, focusing on cooling behavior and resulting mechanical properties.

It can be seen from previous literatures that vegetables oils have been used as lubricants in their natural forms but on the negative side they lack sufficient oxidative stability for use as lubricants. The low oxidative stability means, if untreated, the oil will oxidize rather quickly during use, becoming thick and polymerizing to a plastic-like consistency. Therefore, chemical modification of oils and the use of antioxidants can address this problem, nonetheless increasing the cost. Future work must focus on systematic formulation optimization using Design of Experiments (DOE), long-term stability studies, and comprehensive life-cycle assessments to facilitate widespread industrial adoption, hence more work needs to be done in these areas.

4.0 **CONCLUSIONS**

The review leads to the following key conclusions:

i. Vegetable seed oil-based metalworking fluids (MWFs) have been shown to be technically feasible, environmentally superior alternatives to conventional mineral-oil formulations across a wide range of machining operations. Their polar fatty-acid structure provides high inherent lubricity, good wettability, and biodegradability, enabling significant reductions in surface roughness, cutting temperature, tool wear, and cutting forces relative to dry cutting and, in many cases, compared with mineral oils in turning, milling, drilling, and grinding.

ii. The fluid performance demonstrates that both base-oil chemistry and formulation architecture depends on: chemically modified oils (e.g., epoxidized systems) and nano-enhanced vegetable oils (with TiO_2, MWCNTs, MoS_2, graphene and related additives) effectively overcome basic limitations in oxidative and thermal stability, while additives like emulsifier, EP/AW, antioxidant, biocide, and corrosion-inhibitor are essential to maintain emulsion stability and tribological effectiveness under industrial conditions.

iii. Advanced application strategies especially Minimum Quantity Lubrication (MQL), and hybrid schemes combining nanofluids with cryogenic or solid-lubricant assistance can reduce fluid consumption by over 90% without sacrificing, and often improving, surface integrity and tool life, provided that cutting parameters and fluid properties are jointly optimized using modern Design of Experiment and multi-response optimization tools such as Taguchi methods, Response Surface Methodology, and Grey Relational Analysis.

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DECLARATION OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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