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Vegetable Oil-Based Cutting Fluids A Comprehensive Review on Overcoming Sustainable Machining Challenges

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Abstract*: In today's environmentally conscious manufacturing sector, there is a significant shift from conventional petroleum-based cutting fluids toward bio-based lubricants for sustainable machining applications. Synthetic cutting fluids pose serious environmental and occupational health concerns, including skin irritation, dermatitis, respiratory disorders, hazardous aerosols, and contamination during handling and disposal. In contrast, vegetable oil-based cutting fluids have emerged as an eco-friendly alternative because of their excellent lubricity, biodegradability, renewability, and low toxicity. Their superior tribological and cooling characteristics contribute to reduced friction, lower cutting temperatures, improved surface quality, and extended tool life during machining operations. This review critically evaluates the potential of vegetable oil-based cutting fluids in achieving sustainable green manufacturing by comparing the performance of various edible and non-edible vegetable oils across different metal cutting processes. The reviewed studies demonstrate that vegetable oils can effectively replace conventional synthetic cutting fluids while maintaining machining performance, reducing environmental impact, lowering operational costs, and supporting cleaner, safer, and more energy-efficient manufacturing practices.*

Keywords: Sustainable Manufacturing; Cryogenic Minimum Quantity Lubrication (CMQL); Vegetable oils; Metal cutting fluids

I. INTRODUCTION

The machining of hardened steels generates excessive heat, tool wear, and poor surface quality. Sustainable lubrication techniques such as Minimum Quantity Lubrication (MQL) have emerged as effective alternatives to conventional cooling methods. This study investigates an ultrasonic atomization-based MQL system using sunflower oil to improve machining performance and tribological behavior of AISI 9310 steel [1]. Compacted Graphite Iron (CGI) is widely used in automotive applications due to its superior mechanical properties but remains difficult to machine. Advanced cooling and lubrication strategies are required to improve tool life and surface quality. This work proposes a hybrid machining approach combining MQL and liquid nitrogen cooling for enhanced turning performance [2]. The manufacturing sector is increasingly focused on reducing energy consumption while maintaining machining efficiency. Eco-friendly lubrication methods have gained attention as sustainable alternatives to conventional flood cooling. This study evaluates the influence of MQL on energy consumption, tool wear, and surface finish during high-speed turning of aluminum alloys [3]. Sustainable machining requires effective lubrication technologies that reduce environmental impact and improve process efficiency. Recent developments in lubricant enhancement techniques have significantly improved cooling and friction reduction capabilities. This review discusses advanced lubrication technologies and their role in promoting sustainable manufacturing practices [4]. Heat generation and friction at the tool-workpiece interface strongly affect machining quality and tool life. Sustainable cooling and lubrication strategies are increasingly being adopted to address these challenges. This study investigates the tribological and cooling characteristics of advanced lubrication systems to enhance machining performance [5]. Vegetable oil-based metalworking fluids have gained popularity due to their biodegradability and environmental benefits. However, their performance under MQL conditions often requires further enhancement. This research explores the addition of nano-graphite and nano-alumina particles to a coconut oil-based fluid to improve lubrication and cooling efficiency [6].

Titanium alloys are difficult-to-machine materials because of their high strength and poor thermal conductivity. Nanofluid-based MQL techniques have shown potential in reducing cutting forces and machining temperatures. This study develops a cutting force model for titanium alloy milling using C60 nanoparticle-enhanced MQL lubrication [7]. Nano Minimum Quantity Lubrication (NMQL) has attracted significant attention for its potential to improve cooling and lubrication during machining. The thermal conductivity of nanoparticles is believed to enhance heat dissipation at the cutting zone. This study experimentally and numerically evaluates the cooling effectiveness of NMQL compared with conventional MQL systems [8]. Nanoparticle-enhanced vegetable oils have emerged as promising cutting fluids for sustainable machining applications. Carbon nanodots can improve the thermal and tribological properties of biodegradable lubricants. This study examines the performance of carbon nanodot-enriched rice bran oil under MQL conditions during milling of additively manufactured 316 stainless steel **[9].** Conventional cutting fluids pose environmental and health concerns in machining industries. Vegetable oils offer a renewable and biodegradable alternative for sustainable manufacturing. This research evaluates palm kernel oil as an MQL cutting lubricant and optimizes machining parameters during turning of AISI 1039 steel using Taguchi-Grey Relational Analysis **[10].** Sustainable and green manufacturing has remained a primary objective for manufacturing industries over the past three decades; however, significant challenges still hinder the achievement of complete sustainability goals [11]. As major stakeholders in resource consumption and environmental impact, manufacturing industries play a crucial role in promoting sustainable development. Many organizations recognize the importance of environmental responsibility and have adopted various strategies to address these concerns. Compared with 2017 levels, global material extraction is projected to double by 2050 (Fig.01). Similar growth trends are anticipated in energy consumption, water utilization, and greenhouse gas emissions, all of which are expected to nearly double by 2050. Furthermore, the current rate of natural resource exploitation exceeds the Earth's regenerative capacity by approximately 1.7 times [12].

Sustainable manufacturing aims to create a future where environmental impacts are minimized or eliminated entirely [13]. Consequently, green manufacturing practices have become an integral component of sustainable production systems, ensuring environmental protection while maintaining economic viability and social responsibility [14]. Among various manufacturing activities, machining operations offer significant opportunities for implementing sustainability through the use of environmentally friendly metal cutting fluids (MCFs).

Machining processes involve the removal of material from a workpiece using cutting tools to achieve the desired shape and dimensions. The energy required for material removal can account for nearly 66% of the total energy consumed during machining operations [15]. A substantial portion of this energy is converted into heat [16], necessitating the application of MCFs to dissipate heat from the cutting zone. Conventionally, MCFs are applied at rates ranging from 10 to 100 L/min [17]. Mineral oil-based cutting fluids dominate the market, accounting for approximately 85% of total MCF consumption. Although effective in machining applications, these petroleum-based fluids pose considerable environmental and health concerns [18].

Mineral oils require careful handling during storage, usage, and disposal due to their adverse environmental effects [19]. Studies conducted within the German automotive sector reported that MCF-related expenses accounted for 7–17% of total machining costs, whereas cutting tools represented only 2–4% of the overall cost [20]. Stringent environmental regulations governing the disposal of cutting fluids further increase the total lifecycle cost of MCFs, from procurement to disposal [21].

Several undesirable consequences are associated with the use of mineral oil-based cutting fluids. These fluids negatively affect both the environment and machine operators [22,23]. Conventional petroleum-based MCFs are non-biodegradable and can cause severe ecological damage. Additionally, prolonged exposure to these fluids poses serious health risks. Workers who regularly come into contact with conventional cutting fluids may experience skin irritation, inhalation of hazardous aerosols, ingestion-related problems, and other occupational health issues [24]. Long-term exposure may also contribute to carcinogenic effects, genetic alterations, and various dermatological disorders. Beyond human health impacts, these fluids contaminate air, soil, and water resources.

MCFs are recognized as a major contributor to occupational illnesses, with nearly 80% of such diseases attributed to toxic substances and microbial contamination present in cutting fluids [25]. Moreover, the total expenditure associated with MCFs, including procurement, maintenance, and disposal, can account for approximately 16% of overall metalworking costs and may increase to 30% when machining difficult-to-cut materials [26].

The disposal cost of conventional cutting fluids often exceeds their purchase price, sometimes reaching four times the original cost of the fluid [27]. Increasingly stringent environmental regulations have accelerated the search for eco-friendly machining solutions, emphasizing the importance of sustainable MCF alternatives [28]. As a result, extensive research has been conducted to investigate the evolution of cutting fluids and identify environmentally responsible alternatives.

Vegetable oils have emerged as one of the most promising substitutes for conventional mineral oil-based cutting fluids. These bio-based lubricants are biodegradable, environmentally friendly, and capable of enhancing machining performance. Consequently, growing interest has been directed toward vegetable oil-based MCFs as sustainable alternatives for machining applications.

Vegetable oils are primarily extracted from plant seeds, including coconut, sunflower, soybean, rapeseed, olive, and palm sources [29]. These renewable lubricants offer excellent biodegradability while significantly reducing waste treatment costs. Research findings indicate that vegetable oils can achieve biodegradation rates ranging from 70% to 100% [30]. Despite these advantages, the industrial adoption of bio-based cutting fluids remains relatively limited. Nevertheless, their consumption has steadily increased, reflecting growing awareness of sustainable manufacturing practices and the expanding market potential of environmentally friendly lubricants.

Therefore, vegetable oils represent a viable alternative to conventional cutting fluids and contribute significantly to sustainable manufacturing. Previous studies have highlighted the potential of vegetable oil-based MCFs in promoting green machining practices [31]. Researchers have further recommended investigations into bio-based fluid formulations, recycling techniques, application methodologies, optimal fluid selection, and quantity optimization to enhance sustainability in machining operations [32]. However, despite growing interest in vegetable oil-based MCFs, comprehensive literature addressing sustainability from environmental, economic, and technical perspectives remains limited. Existing studies often emphasize environmental benefits while providing insufficient consideration of economic feasibility. True sustainability cannot be achieved without economically viable implementation of bio-based cutting fluids. Therefore, the present study adopts a balanced approach by examining the environmental, technical, and economic aspects of vegetable oil-based MCFs, thereby contributing to the advancement of sustainable green manufacturing practices in machining operations.

II. REVIEW METHODOLOGY

The sustainability assessment of eco-friendly metal cutting fluids (MCFs), particularly vegetable oil-based lubricants, can be effectively conducted through a systematic review of both conventional and modern cutting fluids. Analyzing the challenges, limitations, and performance issues associated with existing fluids provides valuable insights and highlights the need for further research on vegetable oil-based alternatives. A comprehensive literature review serves as an essential tool for understanding the research domain and identifying knowledge gaps. The review process is carried out in three stages: review planning, source identification, and knowledge synthesis, ensuring a structured and systematic approach to the preparation of the review article.

2.1 Review planning stage

This stage focuses on the systematic collection of research articles through a well-structured review methodology. Important insights for conducting an effective literature review were obtained from Webster and Watson [29], who emphasized that a rigorously executed review provides a strong foundation for technological advancement and future research directions. By integrating diverse findings and perspectives from previous studies, review articles facilitate the identification and resolution of existing research challenges [30], which forms a key objective of the present study.

A structured and sequential approach was adopted for the review planning process, following the framework proposed by Moher et al. [31]. This methodology comprises four major stages: identification of relevant literature sources, screening of collected databases, assessment of the eligibility of selected studies, and inclusion of the most appropriate publications in the final review. Such a systematic approach enables the comprehensive evaluation of both the advantages and challenges associated with environmentally friendly metal cutting fluids (MCFs).

The planning phase was designed to consolidate contemporary developments, historical advancements, empirical evidence, and significant research findings related to bio-based MCFs. By integrating these diverse contributions, the present review aims to provide a comprehensive understanding of sustainable machining practices and the role of eco-friendly cutting fluids in green manufacturing.

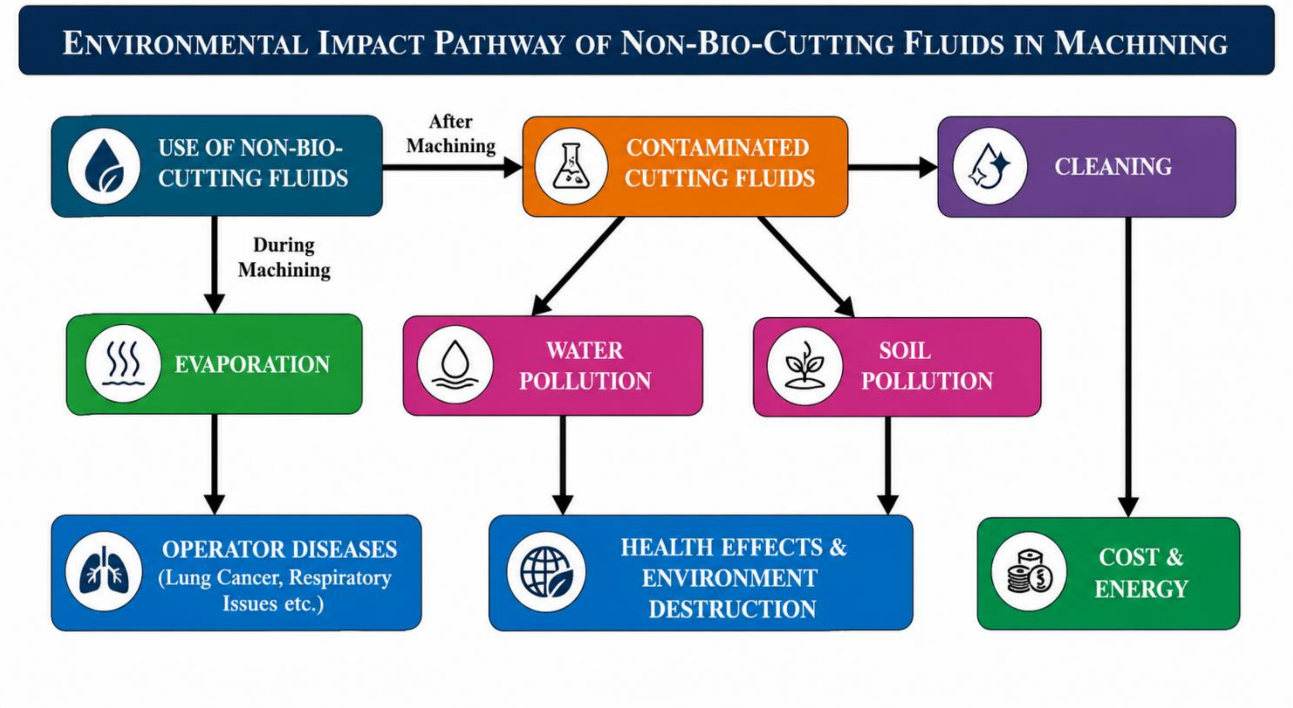

Fig 1. Ecological Threats Associated with the Use of Conventional Cutting Fluids During Machining (from [11])

2.2 Source discovery stage

The literature considered for the present review was collected from a wide range of reputable sources, including Elsevier, Springer, Google Scholar, ScienceDirect and relevant web resources. The selection of research articles and supporting materials was based exclusively on their relevance to the objectives of the review, ensuring that the quality and credibility of the collected information remained uncompromised regardless of the source.

To identify suitable literature, several keywords were employed, including metal cutting fluids (MCFs), vegetable oils, sustainability, green manufacturing, mineral oils, additives, dry machining, minimum quantity lubrication (MQL), and machining processes. Particular emphasis was placed on studies addressing sustainability aspects within machining operations and cutting fluid applications.

A total of 120 resource materials were collected, screened, and evaluated, covering approximately 10 research articles published up to 2018. The review primarily focuses on literature published during the last two decades. The year-wise distribution of the selected publications is illustrated in Fig. 5.

Analysis of the collected literature indicates a growing research interest in environmentally sustainable manufacturing practices using bio degradable oil such as aloe vera, coconut, soybean etc, cleaner production technologies, and green machining solutions. This trend is reflected by the substantial increase in publications during the current decade. Consistent with this observation, approximately 59% of the research contributions included in the review were published during the most recent decade. In comparison, around 34% of the studies were published between 2000 and 2010. Furthermore, nearly 7% of the reviewed works were included to provide from the insights into the development and evolution of metal cutting fluids from same industries survey.

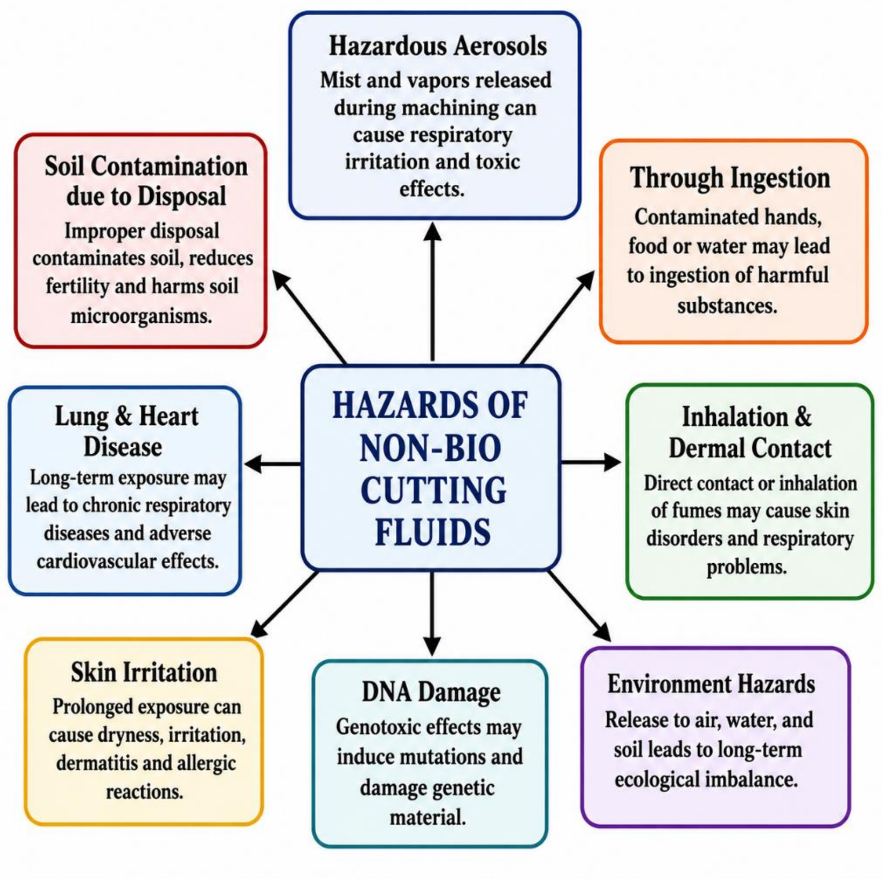

Fig. 2. Health hazards associated with non-bio-cutting fluids in the machining process.[11]

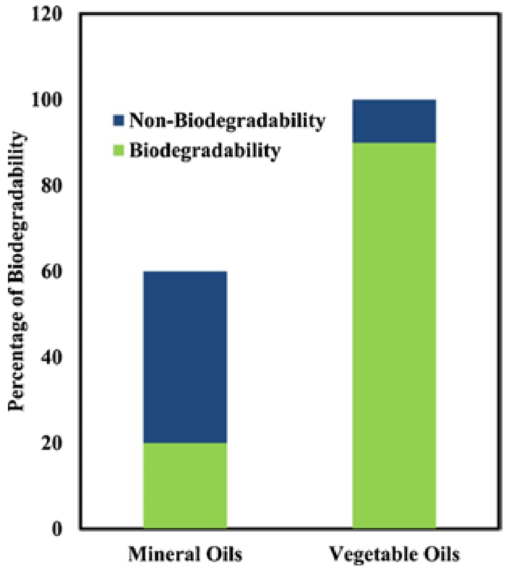

Fig. 3. The superiority of vegetable oils over mineral oils in terms of biodegradability (Image redrawn from [18]).

2.3. Know-how stage

A substantial amount of technical information and research evidence was obtained from the selected publications, providing a comprehensive understanding of machining cutting fluids (MCFs) and their evolution in manufacturing applications. The reviewed studies offer valuable insights into the historical development of MCFs, their progressive adoption in machining operations, and their role in improving machining performance. To ensure systematic presentation and effective interpretation, the collected literature has been organized into different thematic sections based on the scope and objectives of the present review [11–13].

The review begins with a concise overview of machining cutting fluids, followed by a detailed discussion of their classification, performance characteristics, industrial applications, and sustainability aspects. Particular emphasis has been placed on vegetable oil-based cutting fluids because of their increasing importance as environmentally benign alternatives to conventional mineral oil-based lubricants. The review also examines the environmental concerns associated with petroleum-derived cutting fluids, especially their adverse ecological effects and disposal-related challenges, while highlighting the emerging potential of vegetable oils as sustainable machining lubricants [14–16].

To provide a comprehensive perspective, the available vegetable oils have been systematically categorized and individually evaluated based on their machining performance. Different cooling and lubrication mechanisms employed during machining operations are discussed to illustrate the effectiveness of these bio-based fluids under various cutting conditions. Furthermore, the physicochemical properties of vegetable oil-based cutting fluids reported in previous studies have been compiled and summarized to facilitate comparison among different lubricants [17–19].

The advantages and limitations of vegetable oil-based machining cutting fluids are critically analyzed, along with the enhancement techniques proposed by researchers to overcome their inherent shortcomings. These improvement strategies include the incorporation of performance-enhancing additives, formulation modifications, and advanced lubrication approaches aimed at improving thermal stability, oxidation resistance, and tribological characteristics [20–22].

Finally, the review summarizes the major findings reported in the literature and outlines future research directions for the application of vegetable oils in sustainable machining. The increasing industrial demand for eco-friendly cutting fluids, together with stringent environmental regulations and the growing emphasis on cleaner manufacturing technologies, has accelerated research interest in vegetable oil-based lubricants. Consequently, this review provides a comprehensive reference for researchers, industrial practitioners, and the scientific community by identifying current challenges, research opportunities, and future prospects associated with the application of vegetable oil-based machining cutting fluids in environmentally sustainable manufacturing processes [23–26].

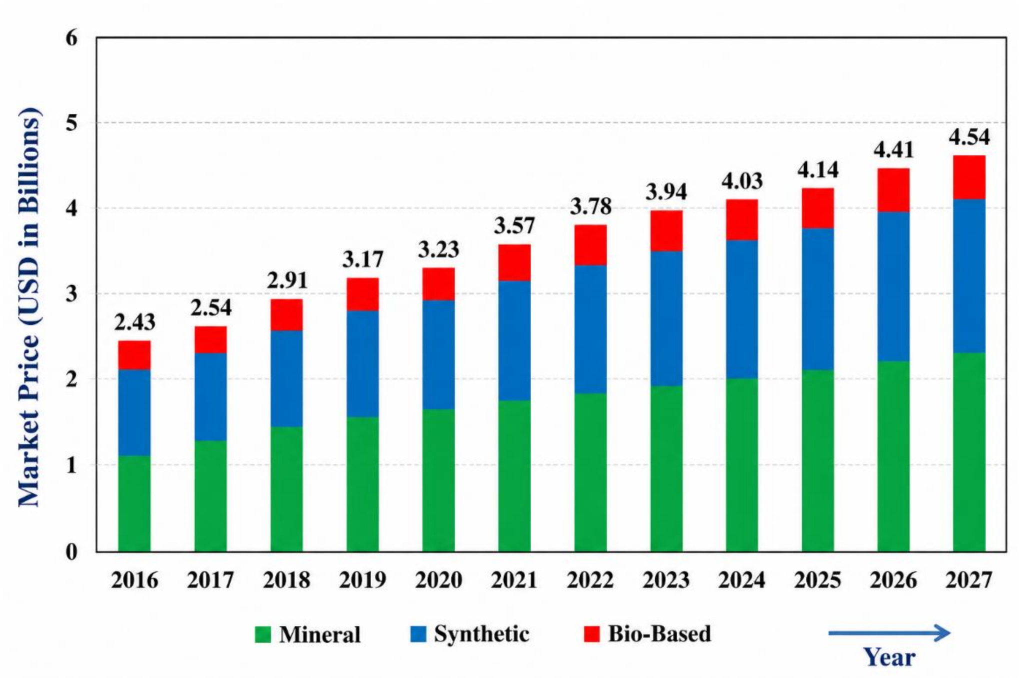

Fig. 4. Market share of MCFs in the United States (US) in Billions (US Dollars) [212].

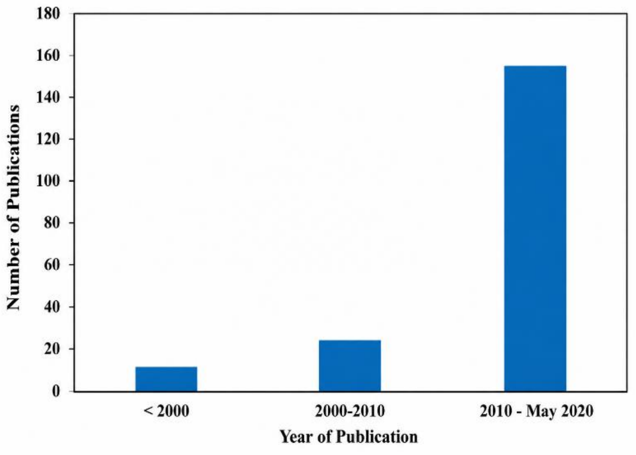

Fig. 5. A scenario of MCFs related publication including vegetable oils. [11]

3. Overview of review works associated with vegetable oils

The growing interest in biodegradable and environmentally sustainable cutting fluids has encouraged several researchers to investigate the application of vegetable oils in metal-cutting operations. Previous review studies have highlighted the potential of vegetable oils such as neem (Melia azadirachta), rice bran (Oryza sativa), and karanja (Pongamia glabra) as eco-friendly alternatives to conventional mineral oil-based cutting fluids. These oils possess desirable characteristics, including high biodegradability, low toxicity, and environmentally safe disposal, making them suitable candidates for sustainable machining applications [11]. Similar observations have been reported for soybean, sunflower, and rapeseed oils, where improved lubrication characteristics and environmentally benign properties have been emphasized for machining processes [12].

A detailed examination of the available review literature revealed that most previous studies concentrated on only a limited number of vegetable oils. Therefore, the present review expands the scope by incorporating information on approximately 14 different vegetable oils, thereby providing a broader and more comprehensive assessment of their machining performance and industrial applicability [13–15].

Several researchers have extensively discussed the technical feasibility of employing vegetable oils as machining cutting fluids (MCFs) for different machining operations. The reported findings consistently demonstrate that vegetable oil-based lubricants can effectively reduce cutting forces, minimize tool wear, improve surface finish, and lower machining temperatures compared with conventional cutting fluids [16,17]. These improvements highlight the growing significance of vegetable oils in achieving sustainable and high-performance machining processes.

Earlier review articles have also investigated the environmental and occupational health implications associated with machining cutting fluids, with particular emphasis on reducing ecological pollution and enhancing operator safety. These studies primarily focused on environmental sustainability and machining performance while giving comparatively less attention to the economic viability of vegetable oil-based cutting fluids [18–22]. Conversely, a limited number of investigations have evaluated the economic aspects of vegetable oil utilization, demonstrating their potential to reduce machining costs while maintaining acceptable machining performance [23,24].

Despite the substantial progress achieved in environmental and technical research, sustainable manufacturing requires an integrated approach that simultaneously considers technical performance, environmental sustainability, and **economic feasibility**. Improvements in machining performance or ecological compatibility alone cannot ensure successful industrial implementation unless they also contribute to the economic competitiveness of manufacturing industries. Consequently, sustainable machining strategies should be developed by balancing these three fundamental aspects to achieve long-term industrial benefits [25–27].

Recognizing this requirement, the present review adopts a holistic perspective by critically examining the technical, environmental, and economic dimensions of vegetable oil-based machining cutting fluids. This balanced approach provides a comprehensive understanding of the current research landscape while identifying future opportunities for the wider adoption of vegetable oils in sustainable machining applications [28–31].

4.Overview of metal cutting fluids (MCFs)

Metal cutting fluids (MCFs) have remained an indispensable component of machining operations for more than two centuries owing to their critical role in enhancing machining efficiency, improving product quality, and extending tool life. Throughout their historical development, MCFs have continuously evolved to satisfy the increasing demands of modern manufacturing, particularly those associated with high-speed machining, difficult-to-machine materials, and sustainable production practices. Their primary functions include reducing friction at the tool–chip and tool–workpiece interfaces, dissipating the substantial heat generated during material removal, facilitating efficient chip evacuation, and protecting both the cutting tool and machined surface against corrosion and premature degradation [43].

Beyond conventional cooling and lubrication, MCFs significantly influence the tribological conditions within the cutting zone. Effective lubrication minimizes adhesive and abrasive wear, suppresses built-up edge (BUE) formation, lowers cutting forces, and improves dimensional accuracy. Simultaneously, efficient heat dissipation limits thermal distortion of the workpiece and reduces thermal softening of cutting tools, thereby enhancing tool life, surface integrity, and overall process stability [44–46]. These functions become increasingly important under modern machining conditions involving elevated cutting speeds, higher feed rates, and greater depths of cut, where excessive heat generation can rapidly accelerate tool wear and deteriorate machined surface quality [47].

Historically, water represented the earliest cooling medium employed during primitive machining and grinding operations because of its excellent heat absorption capability. Subsequently, animal fats such as tallow were introduced to provide improved lubrication where cooling alone was insufficient. As machining technology progressed, straight oils, soap-based emulsions, soluble oils, and chemically formulated cutting fluids were successively developed to satisfy increasingly demanding industrial applications. By the mid-twentieth century, synthetic and semi-synthetic cutting fluids had become widely adopted due to their enhanced cooling performance, corrosion resistance, and longer service life. Continuous improvements in additive technology further enhanced oxidation stability, anti-wear characteristics, microbial resistance, and lubrication efficiency, enabling these fluids to support high-performance machining operations [48,49].

The broad classification of metal cutting fluids is illustrated in Fig. 6. MCFs are generally categorized into three principal groups:

- Oil-based (neat oils): comprising mineral oils, vegetable oils, and animal oils.
- Aqueous-based fluids**:** including solution (synthetic), emulsion (oil-in-water), and semi-synthetic cutting fluids.
- Gas-based coolants/lubricants**:** employing compressed air or other gaseous media for environmentally conscious machining applications.

Among these categories, mineral oil-based fluids have traditionally dominated industrial machining because of their satisfactory lubrication characteristics and commercial availability. However, their poor biodegradability, disposal difficulties, occupational health hazards, and environmental pollution have become major concerns under increasingly stringent environmental regulations [50].

Modern manufacturing industries are simultaneously expected to achieve high productivity, superior product quality, reduced production costs, and minimal environmental impact. These objectives often require machining at higher cutting speeds and material removal rates, inevitably increasing frictional heat generation within the cutting zone. Without adequate cooling and lubrication, excessive temperatures accelerate flank wear, crater wear, oxidation, thermal cracking, dimensional inaccuracies, and deterioration of surface integrity. Consequently, selecting an appropriate lubrication strategy has become a decisive factor in maintaining machining efficiency and product reliability [51].

Surface integrity has emerged as one of the most critical quality indicators in precision manufacturing. Besides improving the aesthetic appearance of machined components, superior surface finish enhances fatigue strength, wear resistance, corrosion resistance, and tribological performance while extending the functional service life of engineering components. Since MCFs directly influence friction, chip formation, and thermal behaviour during machining, they play a decisive role in determining the final surface characteristics of machined parts [52]. Numerous recent investigations have further demonstrated that appropriate lubrication strategies significantly reduce surface roughness, cutting temperature, and tool wear while simultaneously lowering machining energy consumption and improving process sustainability [53–56].

Growing environmental awareness has fundamentally changed the selection criteria for cutting fluids over the past decade. Conventional petroleum-derived MCFs are increasingly being replaced by biodegradable alternatives because mineral oils require stringent handling procedures throughout storage, application, recycling, and disposal. Their prolonged exposure may generate hazardous aerosols, skin irritation, respiratory disorders, soil contamination, and water pollution, while disposal costs often exceed the initial purchase cost of the cutting fluid itself [43]. These concerns have accelerated global research toward environmentally benign lubrication technologies such as Minimum Quantity Lubrication (MQL), Nano-MQL (NMQL), ultrasonic-assisted MQL, cryogenic-MQL hybrid systems, and biodegradable vegetable oil-based lubricants, all of which substantially reduce cutting fluid consumption while maintaining or improving machining performance [54–60].

Among biodegradable alternatives, vegetable oils have attracted considerable attention because of their excellent lubricity, high viscosity index, superior film-forming capability, renewable origin, and near-complete biodegradability. Their molecular structure, characterized by long-chain fatty acids with polar ester groups, provides strong adsorption onto metallic surfaces, producing stable lubricating films that effectively reduce friction and wear. In many machining applications, vegetable oils exhibit superior lubricating performance compared with conventional petroleum-based fluids while eliminating many of the associated environmental and health concerns [43,54]. Furthermore, the incorporation of nanoparticles, advanced atomization techniques, electrostatic spraying, ultrasonic assistance, and hybrid cooling approaches has further enhanced the cooling and lubrication capabilities of vegetable oil-based MQL systems, extending their applicability to difficult-to-machine alloys including titanium alloys, hardened steels, compacted graphite iron, stainless steels, and aerospace materials [55–60].Within the oil-based category illustrated in Fig. 6, vegetable oils represent one of the most promising sustainable base lubricants for future machining applications. Unlike mineral and animal oils, vegetable oils combine excellent tribological behaviour with biodegradability, low toxicity, renewability, and reduced carbon footprint. Among the available vegetable oils, non-edible oils such as neem oil are particularly attractive because they do not compete with food resources while offering high lubricity, oxidative stability after suitable formulation, and significant potential for environmentally sustainable turning operations under MQL conditions. Consequently, neem oil-based MQL has emerged as a promising research direction capable of simultaneously improving machining performance, reducing environmental burden, and supporting the transition toward sustainable manufacturing.

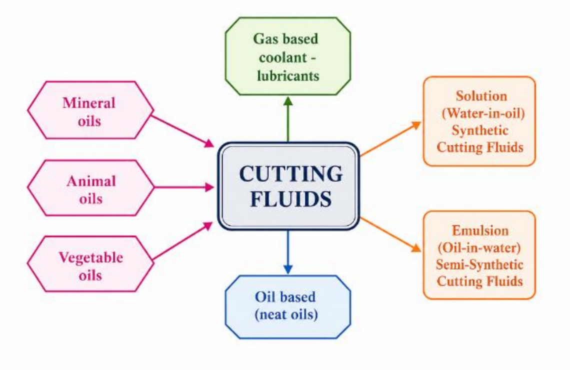

Fig. 6. Broad classification of MCFs for machining applications (Inspired from [8]).

5. Vegetable oils

5.1. Overview of vegetable oils

Vegetable oils have been utilized as lubricants since ancient civilizations owing to their natural lubricating ability, although documented evidence of their application in metal cutting operations is absent from early historical records. Initial lubrication practices primarily involved animal fats and plant-derived oils for reducing friction between contacting surfaces in mechanical systems rather than for machining processes [53]. One of the earliest documented references dates back to the eighteenth century, when around 1735, tallow and vegetable oils were recommended as lubricants for rough metallic surfaces to minimize friction and wear [54].

The evolution of metal cutting fluids during the early twentieth century substantially altered the use of natural oils in machining. Between 1900 and 1950, petroleum-derived straight mineral oils, lard- and tallow-based lubricants, and marine oils such as sperm and fish oils became increasingly popular because of their commercial availability, improved oxidation stability, and suitability for industrial-scale manufacturing. Consequently, vegetable oils gradually lost their prominence as machining lubricants despite their excellent tribological characteristics [55]. During this period, Hutton introduced an important advancement by developing a water-soluble cutting fluid formulation comprising washed sulfonated castor oil and unsaponified fatty oil, which received patent protection and represented one of the earliest attempts to improve lubrication and cooling performance through natural oil-based emulsions [33].

Further progress in colloidal chemistry and surfactant science facilitated the development of stable soluble cutting fluids derived from natural fatty oils. These innovations significantly enhanced emulsion stability, lubrication efficiency, and corrosion resistance, expanding the applicability of bio-based cutting fluids in machining operations [55]. Between 1942 and 1948, Shaw's pioneering investigations into boundary lubrication demonstrated that free fatty acids chemically react with metallic surfaces to produce metallic soaps and tribochemical compounds such as sulphides and chlorides. These reaction products form protective boundary films that reduce friction, suppress adhesive wear, and improve tool life under severe machining conditions [33]. These findings established the scientific basis for employing vegetable oils as effective lubricants in metal cutting applications.

Although petroleum-based cutting fluids dominated industrial machining for several decades due to their lower production cost and better oxidative stability, growing environmental concerns, increasingly stringent disposal regulations, and occupational health issues have redirected research towards sustainable lubrication technologies. Consequently, vegetable oils have re-emerged as viable alternatives because they are renewable, biodegradable, non-toxic, and capable of delivering superior lubricity compared with conventional mineral oils [43].

Comprehensive reviews by Shashidhar and Jayaram identified vegetable oils as promising eco-friendly substitutes for conventional metal cutting fluids, emphasizing their potential to simultaneously improve machining performance and environmental sustainability [23]. More recent investigations have further strengthened this perspective by demonstrating that vegetable oil-based Minimum Quantity Lubrication (MQL) systems significantly reduce cutting forces, tool wear, cutting temperature, surface roughness, and energy consumption while requiring only a fraction of the lubricant used in conventional flood cooling systems [56–60]. In addition, recent developments involving nano-enhanced vegetable oils, ultrasonic-assisted MQL, electrostatic MQL, and hybrid cryogenic-MQL techniques have further improved the cooling and lubrication performance of bio-based cutting fluids, making them suitable for machining advanced engineering materials including titanium alloys, hardened steels, stainless steels, compacted graphite iron, and aerospace alloys [57–60].

Among various renewable lubricants, non-edible vegetable oils have attracted particular interest because they eliminate competition with edible oil resources while supporting sustainable manufacturing objectives**.** Neem oil, in particular, possesses favourable physicochemical and tribological characteristics, including high lubricity, strong film-forming ability, biodegradability, and low environmental toxicity, making it a highly promising base lubricant for MQL-assisted turning operations. Consequently, ongoing research is increasingly focused on optimizing neem oil formulations and additive technologies to further enhance machining efficiency, prolong tool life, improve surface integrity, and promote environmentally responsible manufacturing practices

Table 1. Comparative characteristics of major metal cutting fluid categories

	Mineral Oil	**Synthetic**	**Semi-Synthetic**	**Vegetable Oil**	**Neem Oil-Based MQL**
Lubricity	High	Medium	High	Very High	Excellent
Cooling Ability	Medium	Excellent	High	Medium	High (MQL-assisted)
Biodegradability	Poor	Moderate	Moderate	Excellent	Excellent
Toxicity	High	Moderate	Moderate	Very Low	Very Low
Environmental Impact	High	Medium	Medium	Low	Very Low
Sustainability	Low	Moderate	Moderate	High	Very High

5.2. Categorization of vegetable oils

The growing interest in vegetable oil-based metal cutting fluids has necessitated a systematic classification to facilitate their selection for diverse machining applications. A comprehensive categorization of vegetable oils was proposed by Mannekote *et al.*, providing an organized framework based on oil origin, commercial availability, and end-use applications. Such a classification not only improves the understanding of bio-lubricants but also assists researchers and manufacturing engineers in selecting suitable vegetable oils according to machining requirements, physicochemical properties, availability, sustainability, and economic feasibility [38]. The complete classification of vegetable oils is illustrated in Fig. 7**.**

The first classification is based on the source of oil extraction**,** where vegetable oils are grouped into tree crop oils**,** annual crop oils, and by-product oils**.** Tree crop oils are extracted from perennial plants such as coconut, palm, and olive, which generally provide a stable annual yield and possess favourable lubrication characteristics because of their relatively high fatty acid content. Annual crop oils are obtained from seasonal agricultural crops including sunflower, groundnut, rapeseed, and similar oil-bearing plants. Their production largely depends on annual cultivation cycles and climatic conditions. The third category comprises by**-**product oils, which are recovered from agricultural processing residues. Rice bran oil and soybean oil are typical examples of this group, offering an economically attractive and resource-efficient alternative by utilizing agricultural by-products that would otherwise have limited industrial value [38].

Another important basis for classification is the commercial availability of vegetable oils. Oils such as coconut, sunflower, soybean, palm, and groundnut are produced on a large commercial scale and are therefore categorized as major vegetable oils because of their widespread availability and relatively lower market cost. In contrast, oils including avocado, candlenut, apricot kernel, and almond are classified as minor vegetable oils owing to their comparatively limited production and specialized applications. The availability of a particular vegetable oil directly influences its industrial adoption, production cost, and long-term feasibility as a sustainable metal cutting fluid [38].

Vegetable oils are further classified according to their end-use applications into edible and non-edible oils**.** Edible vegetable oils, including sunflower, coconut, soybean, palm, and groundnut oils, are extensively utilized in food processing and human consumption. Although these oils exhibit excellent lubrication characteristics, their large-scale application in machining raises concerns regarding food security, agricultural resource allocation, and economic sustainability. Consequently, their use as industrial lubricants has become increasingly restricted despite their favourable tribological performance [43].

In contrast**,** non-edible vegetable oils have emerged as the preferred choice for sustainable machining because they do not compete with food resources while offering comparable or superior lubrication properties. Oils such as neem**,** jatropha**,** castor**,** and jojoba possess excellent biodegradability, strong lubricating ability, and low environmental toxicity, making them highly attractive as base oils for environmentally benign metal cutting fluids [43,53]. Their naturally occurring polar fatty acid molecules promote the formation of durable lubricating films at the tool–chip interface, thereby reducing friction, cutting forces, tool wear, and surface damage during machining operations. Furthermore, recent developments in Minimum Quantity Lubrication (MQL), nano-enhanced Consequently, the present review focuses on evaluating the machining performance of non-edible neem oil-based MQL systems**,** highlighting their potential to replace conventional petroleum-based cutting fluids while MQL (NMQL), ultrasonic-assisted MQL, and electrostatic MQL have further enhanced the machining performance of non-edible vegetable oils, extending their applicability to high-speed machining and difficult-to-machine engineering materials [56–60].

Among the non-edible oils, neem oil has attracted significant attention because of its abundant availability in many tropical countries, renewable origin, excellent lubricity, biodegradability, antimicrobial characteristics, and favourable tribological behaviour. These attributes make neem oil an especially promising candidate for sustainable MQL applications in turning operation simultaneously improving machining efficiency and reducing environmental impact.

5.3. Vegetable oils as MCFs

Vegetable oils have emerged as one of the most promising environmentally benign alternatives to conventional petroleum-based metal cutting fluids because of their unique physicochemical, tribological, and biodegradable characteristics. Their effectiveness as machining lubricants primarily originates from the presence of triglyceride molecules containing long-chain fatty acids with polar ester functional groups, which exhibit a strong affinity for metallic surfaces. During machining, these polar molecules readily adsorb onto the tool and workpiece surfaces, forming a stable boundary lubricating film that minimizes direct metal-to-metal contact. This protective tribofilm significantly reduces friction, adhesive wear, and seizure while improving the overall tribological conditions within the cutting zone [43,56].

The adsorption behaviour of vegetable oils plays a decisive role in enhancing machining performance. The polar ester groups chemically interact with metallic surfaces, producing a durable lubricating layer capable of withstanding the severe pressure and temperature conditions encountered during metal cutting. Consequently, friction at the tool–chip and tool–workpiece interfaces is substantially reduced, leading to lower cutting forces, decreased heat generation, suppression of built-up edge (BUE) formation, and improved dimensional accuracy. Reduced friction also minimizes crater wear and flank wear, thereby extending tool life and enhancing the surface integrity of machined components [43,53,56–60].

Besides their excellent lubricating performance, vegetable oils possess several characteristics desirable for sustainable machining, including high lubricity, excellent biodegradability, low toxicity, renewable origin, high viscosity index, and superior film-forming capability. A high viscosity index enables the lubricant to maintain a stable lubricating film over a wide operating temperature range, ensuring consistent lubrication even under varying machining conditions. Furthermore, the biodegradable nature of vegetable oils considerably reduces environmental pollution and disposal costs while minimizing occupational health hazards commonly associated with petroleum-based cutting fluids [43].

Effective lubrication simultaneously contributes to thermal management during machining. By reducing frictional resistance, vegetable oils decrease the amount of heat generated at the cutting interface, thereby lowering cutting temperatures and reducing the energy required for material removal. Consequently, machining operations experience lower cutting forces, reduced tool wear, improved chip flow, enhanced surface finish, and better dimensional accuracy. Numerous recent investigations have demonstrated that vegetable oil-based Minimum Quantity Lubrication (MQL) significantly improves machinability by reducing surface roughness, tool wear, cutting temperature, and energy consumption compared with dry and conventional flood machining conditions [56–60].

In addition to lubrication, vegetable oils provide excellent corrosion protection by forming protective films over both cutting tools and machined surfaces. These films inhibit oxidation and moisture-induced corrosion, thereby extending the service life of tooling and improving the durability of machined components. However, despite these advantages, neat vegetable oils possess relatively low thermal conductivity and limited cooling capability compared with water-based cutting fluids. Under high-speed or heavy-duty machining conditions, excessive heat accumulation may occur, increasing the risk of oxidation, thermal degradation, smoke generation, and, in extreme cases, flammability. Therefore, neat vegetable oils are generally more suitable for machining operations involving relatively low cutting speeds and moderate cutting loads, where lubrication plays a more dominant role than cooling [53].

From an industrial productivity perspective, restricting machining to low-speed conditions is often economically impractical. Consequently, vegetable oils are rarely employed in their unmodified form for modern manufacturing applications. Instead, their performance is enhanced through the incorporation of carefully selected additives and advanced formulation techniques. Common additive categories include fatty lubricity improvers, extreme-pressure (EP) additives, viscosity modifiers, oxidation inhibitors, corrosion inhibitors, anti-foaming agents, antimicrobial additives, and odor-control agents. These additives improve lubrication, oxidation stability, thermal resistance, and storage life while extending the operating range of vegetable oil-based cutting fluids [43].

Among these additives, extreme-pressure additives containing phosphorus, sulphur, or chlorine play a particularly important role during severe machining operations. Under elevated temperature and pressure, these additives chemically react with metallic surfaces to produce thin tribochemical films composed of metallic phosphides, sulphides, or chlorides. These protective boundary layers effectively reduce friction and adhesive wear at the tool–chip interface, thereby improving tool life and machining stability under demanding cutting conditions [58].

The overall performance of vegetable oil-based metal cutting fluids depends primarily on three interrelated factors: (i) the base vegetable oil**,** (ii) the type and concentration of additives**,** and (iii) the formulation methodology used to prepare the cutting fluid. The interaction among these three components determines essential properties such as viscosity, thermal conductivity, oxidation stability, emulsion stability, lubricity, wettability, and cooling efficiency. Typical combinations of base oils, additives, and formulation approaches employed in vegetable oil-based MCF development are illustrated in Fig. 8 [59].

Although vegetable oils generally exhibit superior lubricating performance compared with conventional mineral oils and many synthetic cutting fluids, their relatively poor thermo-oxidative stability remains one of the principal limitations restricting widespread industrial adoption. The unsaturated fatty acid chains present in vegetable oils are susceptible to oxidative degradation at elevated temperatures, leading to viscosity changes, polymerization, sludge formation, and deterioration of lubrication performance during prolonged machining operations [43]. To overcome these limitations, several chemical modification techniques—including esterification, transesterification, epoxidation, and hydrogenation—have been successfully employed to improve oxidative stability, thermal resistance, storage life, and overall machining performance without compromising biodegradability [53]. Recent advances in sustainable lubrication technologies have further expanded the applicability of vegetable oils through nano-enhanced MQL (NMQL)**,** ultrasonic-assisted MQL (UMQL)**,** electrostatic MQL (EMQL)**,** and hybrid cryogenic-MQL systems. The incorporation of nanoparticles such as graphite, Al_2O_3, graphene, C_{60} fullerene, carbon nanodots, and other nano-additives has significantly improved the thermal conductivity, anti-wear behaviour, rolling lubrication mechanism, and heat transfer capability of vegetable oil-based lubricants, enabling their successful application in machining hardened steels, titanium alloys, stainless steels, aluminium alloys, and other difficult-to-machine materials [56–60]. These technological developments have substantially narrowed the performance gap between vegetable oil-based lubricants and

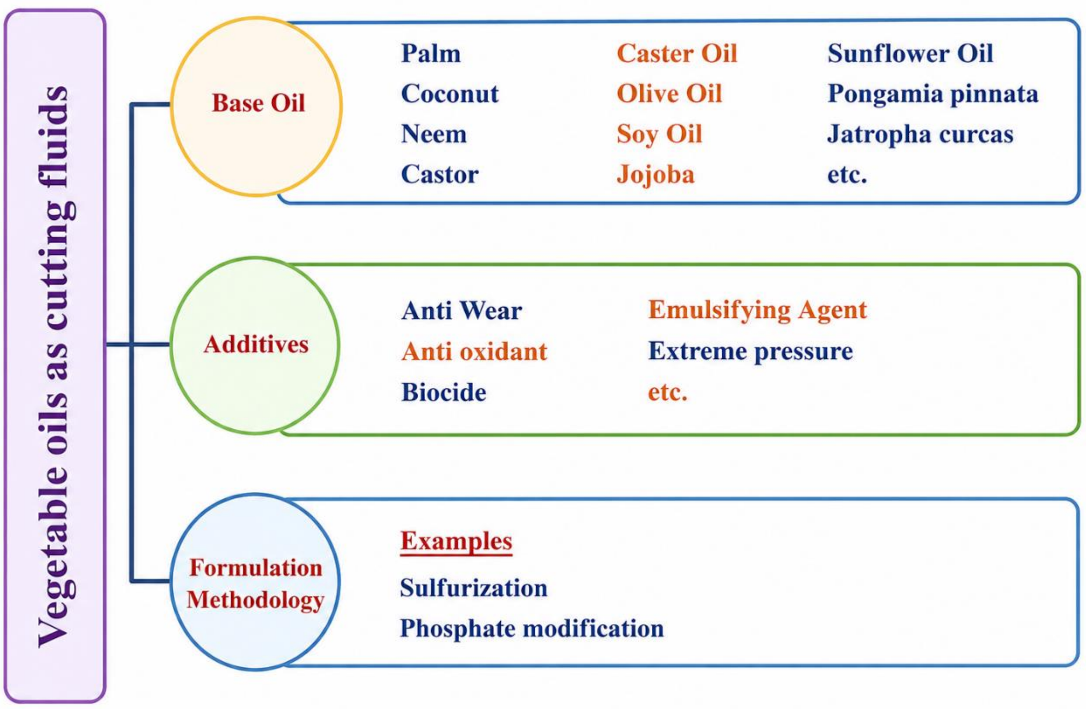

Fig. 7. Vegetable oils as MCFs (Adapted from [49]).

conventional flood cooling systems while preserving the environmental advantages of biodegradable lubricants. Among the available bio-lubricants, non-edible neem oil offers exceptional potential as a sustainable base fluid for MQL applications. Its inherent lubricity, strong adsorption capability, biodegradability, and environmentally benign nature, combined with suitable additive technology and advanced MQL delivery systems, make neem oil a highly promising replacement for petroleum-based cutting fluids in turning operations. Consequently, optimizing neem oil formulations represents an important research direction for achieving high machining performance while simultaneously advancing sustainable and green manufacturing practices.

5.3.1. Additives- part of vegetable oils for machining applications

The performance of vegetable oil-based metal cutting fluids can be significantly enhanced through the incorporation of suitable additives. Although vegetable oils inherently possess excellent lubricity and biodegradability, their relatively poor thermo-oxidative stability, limited cooling capability, and susceptibility to degradation under severe machining conditions restrict their direct industrial application. Consequently, additives have become indispensable constituents of modern bio-based metal cutting fluids, improving lubrication performance, oxidation resistance, thermal stability, corrosion protection, and service life while extending the applicability of vegetable oils to high-speed and high-load machining operations [47].

The concentration of additives plays a decisive role in determining the overall performance of vegetable oil-based lubricants. Depending on the machining application and formulation strategy, additive content may vary considerably. Previous investigations have reported additive concentrations ranging from 5 wt.% to 25 wt.%, with lower concentrations often providing substantial improvements in tribological performance. Experimental studies have further demonstrated that increasing the additive concentration beyond approximately 5 wt.% generally produces only marginal improvements in friction and wear characteristics, indicating that an optimum concentration exists for achieving maximum lubrication efficiency while maintaining formulation stability and economic feasibility [47,57,58].

Commercial lubricant additives are primarily formulated using compounds containing sulphur, phosphorus, or zinc, each contributing specific tribological and chemical characteristics under machining conditions. Based on their functional role, additives are commonly classified into several categories, including anti-wear additives, extreme-pressure (EP) additives, antioxidants, emulsifying agents, corrosion inhibitors, viscosity modifiers, anti-foaming agents, and biocides [59]. The synergistic interaction between these additives and the vegetable oil base fluid enables the formulation of high-performance biodegradable cutting fluids capable of satisfying diverse machining requirements.

Among these, anti-wear and extreme-pressure additives are particularly important during severe machining operations involving elevated contact stresses and temperatures. Under such conditions, sulphur-, phosphorus-, or chlorine-containing compounds chemically react with freshly exposed metallic surfaces to generate thin tribochemical films composed of metallic sulphides, phosphides, or chlorides. These protective boundary films effectively separate the tool and workpiece surfaces, reducing adhesive wear, lowering friction, suppressing seizure, and significantly extending cutting tool life [60]. Antioxidants, on the other hand, retard oxidative degradation of vegetable oils by inhibiting free-radical reactions responsible for viscosity increase, sludge formation, and lubricant deterioration during prolonged machining. Similarly, emulsifiers improve the stability of oil-based emulsions, while biocides inhibit microbial growth, thereby increasing storage stability and service life of biodegradable cutting fluids [59].

Recent developments have also introduced ionic liquids as multifunctional lubricant additives for vegetable oil-based MQL systems. Owing to their excellent thermal stability, negligible volatility, and outstanding lubricating properties, ionic liquids substantially improve friction and wear behaviour even at room temperature. Their unique ionic structure promotes the formation of durable boundary films while simultaneously reducing friction coefficients and enhancing load-carrying capacity. Consequently, ionic liquid additives have emerged as promising environmentally friendly alternatives to conventional sulphur- and chlorine-containing extreme-pressure additives [61].

Understanding the tribological behaviour of additives is essential for optimizing vegetable oil-based metal cutting fluids. During machining, additives continuously interact with freshly generated metallic surfaces, oxide films, hydroxide layers, and metallic ions produced at the tool–chip interface. These tribochemical interactions largely determine the effectiveness of lubrication, wear protection, and friction reduction mechanisms [47]. Depending on their chemical structure, lubricant additives are broadly categorized into ionic and non-ionic compounds. Ionic additives primarily interact with metallic ions generated during machining, whereas non-ionic additives preferentially adsorb onto oxide and hydroxide surfaces. These adsorption processes form stable molecular boundary films that protect newly exposed metallic surfaces from direct contact, thereby minimizing friction, adhesive wear, and surface damage [62].

One of the most significant functions of lubricant additives is their ability to prevent adhesive weldment between the cutting tool and workpiece. During machining of ductile and difficult-to-machine materials such as aluminium alloys, titanium alloys, and stainless steels, fresh metallic surfaces are continuously generated after chip separation. These highly reactive surfaces possess thin oxide layers that readily form strong metallic bonds under elevated pressure and temperature, leading to built-up edge (BUE), material adhesion, unstable cutting, and accelerated tool wear. Additives rapidly adsorb onto these freshly exposed surfaces, forming protective tribofilms that inhibit direct metallic contact and effectively suppress adhesive bonding [62,63]. This mechanism is particularly important in MQL machining, where the limited quantity of lubricant necessitates highly efficient boundary lubrication.

In addition to tribological protection, additives influence several physicochemical phenomena occurring within the machining zone. Processes such as adsorption, tribochemical reactions, boundary film formation, Rehbinder effect, surface energy modification, Marangoni flow, capillary penetration, and molecular bonding collectively determine the lubrication efficiency and frictional behaviour of metal cutting fluids [47]. The adsorption of polar additive molecules onto metallic surfaces represents the initial stage of these interactions, followed by tribochemical reactions that continuously regenerate protective boundary layers during machining. Simultaneously, capillary action and Marangoni-driven flow facilitate deeper penetration of lubricant droplets into the tool–chip interface, particularly under Minimum Quantity Lubrication (MQL) conditions, thereby enhancing cooling and lubrication efficiency [56,59].

At the microscopic level, intense plastic deformation occurring adjacent to the chip formation zone generates localized microcracks and severe lattice distortion within the workpiece material. The nature of additive–metal interaction influences crack propagation, dislocation movement, and localized frictional behaviour within these highly stressed regions. Furthermore, tribochemical interactions between additives and metallic surfaces may also modify the electrical and surface properties of the workpiece, thereby influencing oxidation behaviour, surface energy, and long-term corrosion resistance [62,63]. Consequently, the combined action of the base vegetable oil and appropriately selected additives governs the overall tribological performance, machining stability, and service life of biodegradable metal cutting fluids.

Recent advancements in sustainable lubrication technologies have further enhanced additive performance through the incorporation of nanoparticles such as graphite, graphene, Al_2O_3, carbon nanodots, fullerene (C_{60}), and other nano-additives into vegetable oil-based MQL systems. These nano-additives improve thermal conductivity, rolling lubrication mechanisms, anti-wear behaviour, and tribofilm stability while simultaneously reducing cutting forces, tool wear, cutting temperature, and surface roughness [56–60]. Such developments have substantially improved the industrial applicability of vegetable oil-based lubricants for machining advanced engineering materials while preserving their environmental benefits.

For non-edible neem oil-based MQL, additive technology assumes even greater importance because appropriate additive selection can compensate for limitations associated with oxidative stability and thermal resistance while preserving the inherent advantages of neem oil, including excellent lubricity, biodegradability, and environmental compatibility. Therefore, optimizing additive composition remains a critical research direction for developing high-performance, sustainable metal cutting fluids capable of replacing conventional petroleum-based lubricants in modern turning operations.

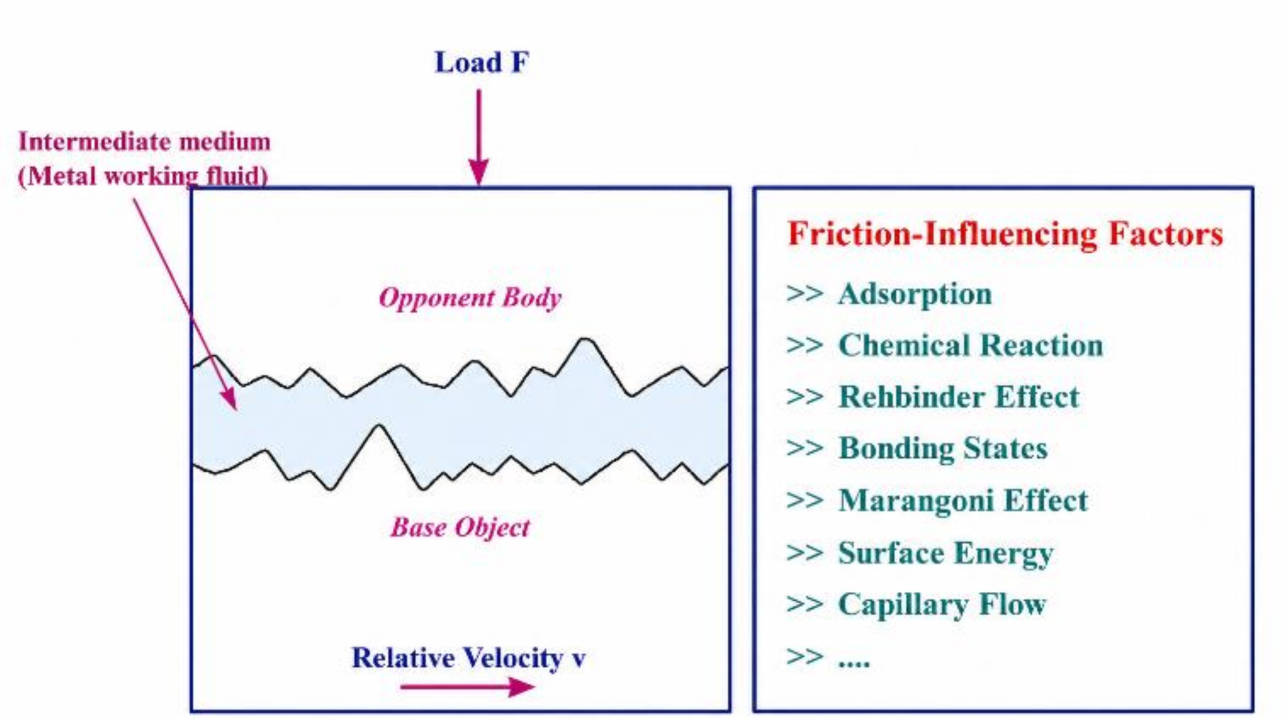

Fig. 8. The intermediator role of MCFs (Image redrawn from [37]).

Table 2. Functional classification of additives used in vegetable oil-based metal cutting fluids

Additive Type	Primary Function	Typical Mechanism	Machining Benefit
Anti-wear	Reduce wear	Protective boundary film	Longer tool life
Extreme-pressure (EP)	Prevent seizure	Sulphide/phosphide film formation	Lower friction under high load
Antioxidant	Improve oxidation stability	Inhibits oxidative degradation	Longer fluid life
Emulsifier	Stabilize emulsions	Improved dispersion	Better cooling and lubrication
Corrosion inhibitor	Prevent oxidation	Surface passivation	Improved workpiece protection
Biocide	Suppress microbial growth	Biological inhibition	Longer storage life
Ionic liquid	Reduce friction and wear	Stable ionic tribofilm	Enhanced tribological performance
Nano-additives	Improve thermal conductivity and lubrication	Rolling effect, tribofilm formation	Reduced temperature, wear, and cutting force

6. Performance of MCFs

The performance of metal cutting fluids (MCFs) during machining is governed by the combined influence of the workpiece material, cutting tool, lubricant characteristics, machining parameters, and the lubrication delivery technique. An effective MCF should simultaneously provide efficient lubrication, rapid heat dissipation, corrosion protection, chip evacuation, and surface protection while maintaining its physicochemical stability throughout the machining process. Consequently, the overall effectiveness of an MCF cannot be evaluated solely based on its cooling or lubricating capability, but rather on its ability to maintain favourable tribological and thermal conditions at the tool–chip–workpiece interface under varying machining environments [47].

The selection of a suitable cutting fluid largely depends on the dominant machining requirement. Oil-based MCFs, particularly vegetable oil-based lubricants, are preferred for applications where boundary lubrication and friction reduction are more critical than cooling. Their strong lubricating film effectively reduces cutting forces, tool wear, and adhesive interaction between the cutting tool and workpiece. Conversely, water-based MCFs possess superior heat dissipation capability because of their high specific heat capacity and thermal conductivity, making them more suitable for machining operations involving excessive heat generation where cooling predominates over lubrication [47]. The continuous pursuit of sustainable manufacturing has further encouraged the adoption of vegetable oil-based Minimum Quantity Lubrication (MQL), which successfully combines the excellent lubricity of bio-based oils with minimal lubricant consumption and significantly lower environmental impact [43].

The performance of an MCF results from a complex combination of physical and chemical interactions occurring continuously within the cutting zone. Although these mechanisms are closely interconnected and difficult to isolate experimentally, understanding their individual contributions is essential for optimizing lubricant formulations. The interaction between lubricant molecules and metallic surfaces primarily occurs through adsorption, which may proceed via physisorption or chemisorption, as illustrated schematically in Fig. 10. In physisorption, additive molecules adhere to metallic surfaces through relatively weak intermolecular forces such as van der Waals interactions, providing temporary boundary lubrication. Chemisorption, in contrast, involves the formation of strong chemical bonds between additive molecules and the metallic surface, producing stable tribochemical films capable of withstanding severe contact pressures and elevated machining temperatures [66–68].

Irrespective of the adsorption mechanism, the effectiveness of boundary lubrication depends on the close molecular interaction between lubricant additives and the contacting metal surfaces. Both intermolecular and intramolecular interactions among additive molecules significantly influence the formation, stability, and durability of the protective tribofilm responsible for reducing friction and wear [69,70]. Consequently, the chemical composition of the base oil, additive chemistry, concentration, and formulation methodology collectively determine the overall tribological performance of vegetable oil-based MCFs.

The chemical state of the metal surface also plays a decisive role in determining the effectiveness of lubricant–surface interactions. During machining, freshly generated metallic surfaces rapidly react with oxygen and moisture to form thin oxide and hydroxide layers. These surface films directly influence adsorption behaviour, tribochemical reactions, corrosion resistance, and boundary film formation. Therefore, the machining performance of a cutting fluid depends not only on its intrinsic properties but also on the surface chemistry of both the cutting tool and workpiece materials [71]. However, because oxide formation and tribochemical reactions occur almost instantaneously under highly dynamic machining conditions, experimentally characterizing these interfaces remains one of the major challenges in understanding lubricant mechanisms.

A representative example of such surface chemistry is the passivation phenomenon observed in materials such as aluminium and stainless steels. These materials naturally develop thin, stable oxide layers that protect the underlying metal from further oxidation while simultaneously influencing lubricant adsorption and tribofilm formation [72]. Surface analytical techniques, including X-ray Photoelectron Spectroscopy (XPS), have confirmed that even highly pure iron surfaces are covered by thin layers of iron oxides and hydroxides, whereas stainless steels exhibit complex oxide films primarily composed of chromium and iron oxides [73]. Similar oxide formations have also been reported for numerous engineering alloys, confirming that the tribological behaviour of metal cutting fluids is strongly influenced by the chemical composition and stability of these naturally occurring surface films [74–76].

Besides surface chemistry, the microstructural characteristics of workpiece materials significantly affect MCF performance. Grain size, crystallographic orientation, phase distribution, hardness, and surface defects influence chip formation, contact stresses, friction behaviour, and lubricant penetration at the tool–chip interface. Numerous experimental investigations involving cutting temperature measurements, tool wear analyses, and surface integrity evaluations have consistently demonstrated that optimized lubrication substantially improves machining performance by reducing thermal loading, minimizing tool wear, enhancing dimensional accuracy, and improving surface finish [77–79]. These improvements become particularly significant during machining of difficult-to-machine materials such as titanium alloys, hardened steels, stainless steels, compacted graphite iron, and nickel-based superalloys.

The service life of a metal cutting fluid is another important factor affecting machining performance. For oil-based MCFs, lubricant degradation primarily occurs through oxidation, thermal decomposition, and prolonged exposure to atmospheric oxygen. These reactions gradually alter viscosity, lubrication characteristics, and chemical stability, ultimately reducing machining efficiency [80,81]. During prolonged machining, continuous interaction between lubricant molecules, freshly generated metallic surfaces, elevated temperatures, and tribochemical reactions further modifies the physicochemical properties of the oil, influencing friction behaviour and lubrication performance [82]. Although oil-based cutting fluids generally exhibit better storage stability than water-based emulsions, improving their oxidative stability remains essential for extending service life under severe machining conditions.

Modern vegetable oil-based lubricants have addressed many of these limitations through chemical modification techniques such as esterification and transesterification, as well as through advanced additive technologies that enhance oxidation resistance, thermal stability, and anti-wear performance [53]. More recently, nano-enhanced vegetable oil-based MQL (NMQL)**,** ultrasonic-assisted MQL (UMQL)**,** electrostatic MQL (EMQL)**,** and hybrid cryogenic-MQL systems have further improved lubricant performance by enhancing atomization, heat transfer, lubricant penetration, and tribofilm stability. Experimental investigations have demonstrated significant reductions in cutting temperature, cutting forces, tool wear, and surface roughness while improving energy efficiency and extending tool life compared with conventional MQL and flood cooling strategies [56–60].

Beyond lubrication and cooling, modern MCFs perform several additional functions that directly influence manufacturing productivity. These include efficient chip evacuation, corrosion protection, cleaning of the cutting zone, temporary insulation or electrical conductivity where required, improved workpiece handling, and enhanced process stability. In advanced manufacturing systems, cutting fluids also contribute to process monitoring and intelligent manufacturing by supporting sensor-based condition monitoring, heat transfer management, and signal transmission within automated machining environments [47].

The historical evolution of metal cutting fluids has been strongly influenced by geographical resource availability, industrial requirements, and environmental regulations. Petroleum-derived lubricants dominated machining throughout much of the twentieth century because of their commercial availability and favourable lubrication properties. However, since the 1980s, growing environmental concerns, stringent disposal regulations, increasing awareness of occupational health hazards, and the global emphasis on sustainable manufacturing have revived research into biodegradable cutting fluids [83]. As a result, vegetable oil-based MQL has emerged as one of the most promising sustainable lubrication technologies capable of simultaneously achieving high machining performance, reduced lubricant consumption, lower environmental impact, and improved economic viability.

Among the various biodegradable lubricants investigated, non-edible neem oil has attracted considerable research interest owing to its excellent lubricity, biodegradability, renewable origin, and favourable tribological behaviour. When employed under optimized MQL conditions and combined with suitable additives or nano-enhancement techniques, neem oil has demonstrated significant potential to replace conventional petroleum-based cutting fluids while improving tool life, reducing cutting temperature, enhancing surface integrity, and supporting environmentally sustainable turning operations.

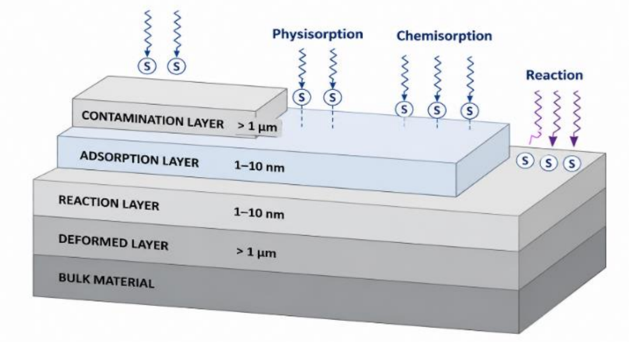

Fig. 9. Possible ways of the reaction of additives with sulphur con tent [56–58,10].

7. Environmental concerns associated with MCFs

Environmental sustainability has become one of the most influential factors driving the transition from conventional petroleum-based metal cutting fluids (MCFs) to biodegradable bio-lubricants. The environmental impact of conventional MCFs extends throughout their entire life cycle—from raw material extraction and formulation to machining, storage, recycling, and final disposal. Consequently, modern cutting fluid development focuses not only on machining performance but also on minimizing environmental burden, protecting worker health, and complying with increasingly stringent environmental regulations [40].

The major environmental concerns associated with conventional metal cutting fluids can be broadly categorized into two principal areas:

- Occupational health and safety of machining personnel
- Waste management, recycling, and environmentally safe disposal of spent cutting fluids

Among these, occupational health represents one of the most critical issues because machine operators are continuously exposed to cutting fluids through direct skin contact, inhalation of oil mist and aerosols, and accidental ingestion during prolonged machining operations. The health hazards associated with conventional petroleum- and synthetic-based MCFs largely arise from their complex chemical composition, including mineral oils, chlorinated paraffins, sulphur- and phosphorus-containing additives, heavy metals, biocides, and other chemically active compounds. The major health issues associated with different MCF constituents are summarized in Table 4.

One of the most serious health concerns is the presence of polycyclic aromatic hydrocarbons (PAHs) in petroleum-derived cutting fluids. Prolonged exposure to PAHs has been associated with skin irritation, allergic dermatitis, chronic inflammatory disorders, and an increased risk of occupational cancers, particularly among machining operators subjected to continuous contact with mineral oil-based lubricants [89]. Similarly, neat mineral oils may contain carcinogenic constituents capable of inducing long-term adverse health effects following repeated exposure [86]. Chlorinated paraffin compounds, commonly employed as extreme-pressure (EP) additives, are known to cause skin disorders while simultaneously generating hazardous vapours that may lead to respiratory irritation and breathing difficulties under prolonged exposure [34]. In addition, additives containing sulphur, chlorine, and phosphorus contribute to the formation of oil mist and airborne aerosols, further increasing the incidence of respiratory disorders among machining personnel [88].

The environmental impact of conventional MCFs extends far beyond the machining environment. During service, cutting fluids undergo continuous physical, chemical, and biological degradation resulting from oxidation, thermal decomposition, contamination with metallic particles, microbial activity, tramp oils, and chemical reactions occurring within the cutting zone. These changes progressively deteriorate lubricant quality while simultaneously increasing the complexity of treatment and disposal [40]. Improper disposal of spent cutting fluids introduces hazardous contaminants into soil and aquatic ecosystems, causing groundwater pollution, disruption of microbial populations, and ecological imbalance. Because enormous quantities of metal cutting fluids are consumed annually in manufacturing industries, their improper disposal poses a significant threat to long-term environmental sustainability [43].

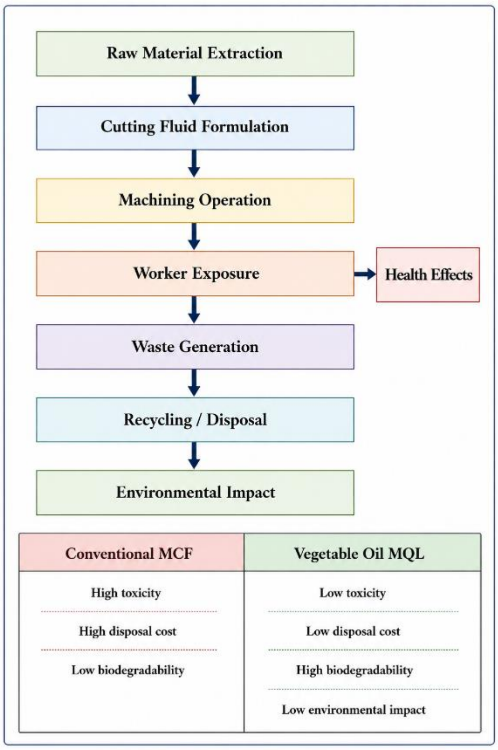

Fig. 10. Life-cycle environmental impact of conventional [8].

Growing environmental awareness has prompted governments worldwide to implement increasingly stringent regulations governing the manufacture, handling, recycling, and disposal of hazardous lubricants. Environmental legislation introduced across Europe, Japan, and several other industrialized nations has substantially restricted the use of toxic lubricant constituents while encouraging the development of biodegradable, environmentally compatible alternatives [90]. These regulatory initiatives have compelled lubricant manufacturers and machining industries to replace hazardous petroleum-based formulations with safer, renewable cutting fluids exhibiting lower toxicity and improved biodegradability. It has been estimated that a substantial proportion of environmental problems associated with metalworking operations can be mitigated through appropriate selection, handling, maintenance, and disposal of cutting fluids [91]. Modern environmental regulations emphasize several essential characteristics for sustainable metal cutting fluids, including high biodegradability, low toxicity, renewable raw materials, reduced environmental persistence, and environmentally responsible disposal after service life [92]. Achieving these objectives has become increasingly important as industries pursue cleaner production technologies and sustainable manufacturing practices consistent with international environmental standards.

Another major challenge associated with conventional MCFs is their high disposal cost. Waste treatment systems require considerable capital investment, sophisticated separation technologies, skilled operation, and continuous monitoring to ensure regulatory compliance. Furthermore, recycling spent cutting fluids often involves multiple stages including filtration, chemical treatment, emulsion breaking, oil recovery, and wastewater purification, making disposal both technically complex and economically expensive [93,94]. In many manufacturing industries, the total lifecycle cost of cutting fluids—including procurement, maintenance, recycling, and disposal—can exceed the initial purchase cost several times over, significantly increasing overall production expenses [43].

These environmental, economic, and regulatory challenges have accelerated global research into sustainable lubrication technologies based on renewable bio-lubricants. Vegetable oil-based metal cutting fluids provide a highly attractive alternative because they possess excellent biodegradability, low toxicity, renewable origin, and superior lubricating characteristics while substantially reducing occupational and environmental hazards [43]. Unlike petroleum-derived lubricants, vegetable oils generally contain simpler chemical compositions with minimal hazardous constituents, thereby reducing the risks associated with operator exposure, accidental leakage, and post-use disposal [95].

The environmental advantages of vegetable oils become even more significant when employed under Minimum Quantity Lubrication (MQL) conditions. MQL drastically reduces lubricant consumption by delivering only a few millilitres of biodegradable lubricant per hour directly to the cutting zone, thereby minimizing waste generation, reducing oil mist formation, lowering disposal costs, and improving workplace cleanliness. Recent studies further demonstrate that advanced lubrication technologies—including nano-enhanced MQL (NMQL), ultrasonic-assisted MQL (UMQL), electrostatic MQL (EMQL), and hybrid cryogenic-MQL systems—simultaneously improve machining performance and environmental sustainability through enhanced lubrication efficiency and reduced lubricant consumption [56–60].

For sustainable manufacturing, the selection of environmentally compatible metal cutting fluids should therefore consider the entire life cycle of the lubricant rather than only its machining performance. Essential criteria include the use of renewable feedstocks, recyclability, biodegradability, minimal toxicity, reduced energy consumption during production, efficient utilization during machining, and environmentally safe disposal after service. Vegetable oils satisfy these requirements more effectively than conventional petroleum-based fluids and therefore represent one of the most promising pathways toward green machining and cleaner production [43].

Among the available bio-lubricants, non-edible neem oil offers additional environmental advantages because it avoids competition with edible oil resources while providing excellent lubricity, biodegradability, antimicrobial characteristics, and low ecological toxicity. These attributes make neem oil particularly suitable for sustainable MQL-assisted turning operations, where high machining performance can be achieved with minimal environmental impact. Consequently, the continued development of neem oil-based formulations, additive technologies, and hybrid lubrication strategies represents an important direction for future environmentally responsible machining research.

Metal cutting fluids (MCFs) are ultimately employed to enhance machining performance by controlling heat generation, reducing friction, improving surface integrity, and extending tool life. Consequently, a comparative evaluation of different cooling and lubrication techniques is essential for understanding their influence on machining performance, energy efficiency, economic feasibility, and environmental sustainability. A comprehensive comparison of dry machining, minimum quantity lubrication (MQL), cryogenic cooling, high-pressure cooling (HPC), and bio-based oil-assisted cooling is presented in Table 7**.** While each technique offers distinct advantages, none can be regarded as universally optimal because their effectiveness depends on machining conditions, workpiece material, cutting parameters, and sustainability requirements.

Chip formation and chip evacuation remain major concerns across all cooling approaches, although the underlying mechanisms differ considerably. Dry machining provides a clean machining environment due to the complete elimination of cutting fluids; however, the absence of lubrication increases tool-chip friction, promotes adhesion, and often results in continuous chips that are difficult to evacuate, thereby deteriorating the machined surface and accelerating tool wear [95,96]. In conventional MQL, the atomized lubricant effectively reduces friction at the tool–chip interface, producing smaller and more controllable chips than dry machining. Nevertheless, the limited quantity of lubricant sometimes provides inadequate cooling under severe cutting conditions, restricting chip breakability during high-speed machining [97]. Recent developments such as ultrasonic-assisted MQL (UMQL), electrostatic MQL (EMQL), and nano-MQL have significantly improved droplet atomization, penetration, and lubricant distribution, thereby enhancing chip breakability and evacuation while maintaining minimal lubricant consumption. These advanced MQL techniques have demonstrated superior tribological performance and improved chip morphology compared with conventional MQL systems.

Cryogenic cooling effectively suppresses excessive cutting temperatures by introducing liquefied gases such as liquid nitrogen or carbon dioxide into the cutting zone. Although the substantial reduction in thermal load minimizes chip adhesion and improves dimensional stability, continuous chip formation may still occur due to insufficient lubrication at the tool–chip interface [98]. Recent hybrid cryogenic-MQL systems successfully overcome this limitation by combining the excellent cooling capability of cryogenic fluids with the superior lubrication characteristics of vegetable-oil-based MQL, resulting in enhanced chip fragmentation, lower cutting forces, improved surface integrity, and extended tool life.

High-pressure cooling and bio-based oil-assisted cooling generally provide the most effective chip evacuation because pressurized coolant or lubricating oil directly penetrates the cutting interface, facilitating chip breakage and reducing tool–chip contact length. However, both techniques introduce post-machining challenges associated with coolant recovery, chip cleaning, and fluid separation during recycling. Bio-based lubricants, despite these limitations, exhibit superior biodegradability and simpler disposal compared with petroleum-based cutting fluids, thereby reducing the environmental burden associated with machining operations.

Surface integrity is another critical performance indicator affected by cooling and lubrication conditions. Dry machining frequently produces inferior surface quality owing to elevated cutting temperatures, severe adhesion, built-up edge (BUE) formation, and unstable chip flow. Conversely, MQL, cryogenic cooling, HPC, and bio-based oil-assisted cooling consistently improve surface finish by minimizing friction and thermal deformation [99–104]. Recent investigations have demonstrated that vegetable-oil-based MQL significantly improves surface roughness owing to its high lubricity, excellent wettability, and strong adsorption characteristics. Furthermore, the incorporation of nanoparticles such as graphite, Al_2O_3, graphene, fullerene (C_{60}), and carbon nanodots into vegetable oils considerably enhances thermal conductivity, tribological properties, and load-carrying capacity, leading to substantial improvements in surface finish and dimensional accuracy compared with conventional MQL.

Tool life is strongly governed by the thermal and tribological conditions developed at the cutting interface. Dry machining generally exhibits the shortest tool life because the absence of cooling and lubrication accelerates abrasive, adhesive, oxidation, and diffusion wear mechanisms [105,106]. Conventional MQL effectively prolongs tool life by reducing friction and maintaining a stable lubricating film between the tool and workpiece. Advanced MQL variants, including ultrasonic-assisted, electrostatic-assisted, and nano-enhanced MQL, further enhance tool life by improving atomization efficiency, increasing lubricant penetration, and forming durable tribofilms that reduce direct metal-to-metal contact. Cryogenic cooling effectively suppresses thermal wear through rapid heat extraction, whereas hybrid cryogenic-MQL systems further improve tool longevity by simultaneously providing efficient cooling and lubrication. Although HPC efficiently removes heat and chips, severe mechanical erosion caused by high-velocity coolant jets and flank wear may still limit tool life under prolonged machining conditions [107]. Among all the cooling techniques reviewed, vegetable-oil-assisted MQL consistently exhibits one of the highest improvements in tool life owing to its superior lubricating capability, excellent film-forming characteristics, and environmentally benign chemistry.

Energy efficiency has become an increasingly important criterion in sustainable manufacturing. Each cooling strategy contributes to energy conservation through different mechanisms while simultaneously introducing unique energy-related challenges. Dry machining eliminates coolant pumps, filtration units, and circulation systems, thereby reducing auxiliary energy requirements [108]. However, higher cutting forces and increased spindle power frequently offset these savings, particularly during machining of hardened or difficult-to-machine materials [100]. MQL substantially reduces pumping energy because only a few millilitres of lubricant are delivered per hour. Nevertheless, compressed-air generation and atomization systems require additional electrical power [27]. Recent investigations have reported that optimized MQL strategies reduce overall machining energy consumption by approximately 20% while simultaneously decreasing tool wear and improving machining quality compared with dry machining.

Cryogenic cooling provides excellent thermal management and improves machining efficiency; however, cryogen production, liquefaction, storage, and transportation require considerable energy input [30,110]. HPC conserves machining energy primarily through reduced cutting forces and efficient chip evacuation [111], although high-pressure pumping and coolant recycling systems increase auxiliary energy consumption. Similarly, vegetable-oil-assisted MQL lowers machining energy by reducing friction and cutting forces while maintaining stable lubrication even at elevated cutting speeds [25,103]. Although bio-lubricant production requires additional energy during extraction and processing, these expenditures are partially compensated by lower coolant consumption, simplified recycling, reduced waste treatment, and improved overall sustainability. Recent CFD investigations further indicate that the primary advantage of nano-MQL arises from enhanced tribological behaviour rather than significantly improved cooling performance, suggesting that friction reduction remains the dominant contributor to energy savings.

Economic feasibility also varies significantly among the investigated cooling techniques. Dry machining minimizes direct coolant-related expenses by eliminating fluid procurement, storage, maintenance, and disposal costs [30,108]. Nevertheless, increased tool wear, inferior surface quality, and higher machining energy often increase the overall production cost when machining difficult materials [27]. MQL offers substantial economic advantages through minimal lubricant consumption, reduced coolant handling, simplified chip recycling, and lower disposal costs [22,104]. Although specialized MQL equipment requires relatively high initial investment [109], the long-term reduction in coolant usage and tool replacement costs generally offsets this expenditure. Cryogenic machining demonstrates similar characteristics; while improved productivity and tool life reduce operational costs, expensive cryogenic infrastructure and continuous cryogen supply significantly increase capital and operating expenditures [29,101,105]. HPC enhances production efficiency and supports high material removal rates but requires costly pumping systems and sophisticated maintenance [106,107]. Vegetable-oil-assisted cooling generally incurs higher lubricant acquisition costs than conventional mineral oils; however, enhanced machining performance, extended tool life, regulatory compliance, simplified disposal, and lower environmental management costs considerably improve its long-term economic viability.

Environmental sustainability represents the principal motivation for developing advanced cooling technologies. Dry machining completely eliminates cutting fluid usage, thereby preventing coolant-related contamination and enabling contamination-free chip recycling [29,108,109]. However, increased cutting temperatures often necessitate additional ventilation to maintain acceptable workplace conditions [99]. MQL substantially reduces coolant consumption, minimizes waste generation, and lowers environmental impact compared with conventional flood cooling [112]. Nevertheless, oil mist formation and airborne particulate emissions require appropriate extraction systems to protect operator health [110,111]. Advanced atomization technologies such as ultrasonic and electrostatic MQL significantly reduce airborne aerosol concentration while improving lubricant utilization efficiency, thereby addressing many occupational health concerns associated with conventional MQL.

Cryogenic cooling produces an exceptionally clean machining environment because cryogenic media evaporate without leaving hazardous residues [27]. However, evaporation losses, storage safety, and handling requirements remain important considerations [113]. HPC contributes to sustainable machining through improved coolant recycling and enhanced productivity but may increase workplace noise and operator exposure if adequate shielding is not provided [114]. Among all the investigated techniques, bio-based oil-assisted cooling demonstrates the highest environmental compatibility because renewable vegetable oils possess excellent biodegradability, low toxicity, high recyclability, and minimal ecological impact [22,47]. Recent investigations involving sunflower oil, rice bran oil, coconut oil, and other biodegradable vegetable oils further confirm that these lubricants significantly reduce environmental burden while simultaneously improving machining performance through superior tribological characteristics.

Overall, the comparative assessment summarized in Table 4 indicates that each cooling strategy possesses inherent strengths and limitations. Dry machining offers the cleanest process but suffers from excessive tool wear and poor surface integrity. MQL provides an effective compromise between lubrication efficiency, economic viability, and environmental sustainability, particularly when biodegradable vegetable oils are employed. Hybrid cryogenic-MQL systems successfully integrate the advantages of cryogenic cooling and MQL, making them highly suitable for machining difficult-to-cut materials. High-pressure cooling remains effective for heavy-duty machining applications but requires significant capital investment and fluid management. Among all the reviewed approaches**,** bio-based vegetable oil-assisted MQL emerges as the most balanced and sustainable machining strategy, combining superior lubrication, excellent surface quality, extended tool life, reduced energy consumption, lower environmental impact, and improved occupational safety. Furthermore, recent advances involving nano-lubricants, ultrasonic atomization, electrostatic spray assistance, and hybrid cryogenic-MQL systems clearly indicate that bio-based MQL technologies represent the next generation of sustainable machining fluids. Therefore, biodegradable vegetable oils can justifiably be regarded as future metal cutting fluid**s** capable of supporting cleaner production, carbon reduction, circular manufacturing, and environmentally responsible machining practices.

8. Eco-friendly biodegradable vegetable oils for machining applications

The growing emphasis on sustainable manufacturing has accelerated the transition from petroleum-derived cutting fluids to biodegradable vegetable oil-based metal cutting fluids (MCFs). Owing to their unique molecular structure and superior tribological characteristics, vegetable oils have emerged as promising alternatives for sustainable machining applications. Their excellent lubricity, biodegradability, renewability, and low toxicity make them highly suitable for minimum quantity lubrication (MQL) systems, where efficient lubrication must be achieved using only a minimal quantity of cutting fluid. Nevertheless, the performance of vegetable oils is largely governed by their physicochemical properties, which are directly related to their molecular composition and fatty acid structure. Consequently, understanding these properties is essential for selecting appropriate vegetable oils for specific machining applications.

Vegetable oils are primarily composed of triglyceride molecules, accounting for nearly 98% of their chemical composition, as illustrated in Fig. 12. A triglyceride molecule consists of three fatty acid chains esterified to a glycerol backbone and generally contains saturated, monounsaturated, and polyunsaturated fatty acids in varying proportions. The relative concentration, molecular arrangement, and degree of unsaturation of these fatty acids significantly influence the lubrication performance, oxidation stability, viscosity, thermal stability, and biodegradability of vegetable oils. Furthermore, factors such as crop variety, cultivation conditions, climatic variations, harvesting techniques, and oil extraction methods considerably affect the final physicochemical characteristics of vegetable oils [135]. Therefore, oils obtained from the same botanical source may exhibit slight variations in machining performance depending on their geographical origin and processing conditions.

The long-chain fatty acid molecules present in vegetable oils possess strong polarity because of their ester functional groups, enabling them to adsorb firmly onto metallic surfaces and form a durable lubricating boundary film. This adsorbed molecular layer effectively separates the contacting surfaces, thereby reducing friction, adhesive wear, and heat generation during machining. Compared with mineral oils, vegetable oils exhibit significantly superior lubricity owing to this strong molecular affinity, making them particularly effective under boundary lubrication conditions encountered in MQL-assisted machining. Recent tribological investigations further demonstrate that the addition of nanoparticles or advanced atomization techniques enhances this boundary lubrication mechanism by improving lubricant penetration and stabilizing the protective tribofilm at the tool–chip interface.

Despite these advantages, certain vegetable oils exhibit relatively poor oxidation stability and limited low-temperature flow characteristics because of their high proportion of unsaturated fatty acids. Under prolonged exposure to elevated machining temperatures, oxidation may increase viscosity, promote gum formation, and shorten lubricant service life. Consequently, chemical modification techniques such as transesterification, epoxidation, hydrogenation, esterification, or blending with suitable synthetic esters and performance additives are frequently employed to improve oxidative stability while preserving the excellent lubricating characteristics of the base oil [127]. Blending vegetable oils obtained from fruits containing longer-chain fatty acids has also been reported as an effective approach for minimizing viscosity fluctuations with temperature, thereby improving flow stability, heat transfer capability, and lubricant transport during machining operations. Such blended bio-lubricants additionally facilitate improved mass transfer characteristics, resulting in lower pumping energy and enhanced cooling efficiency during MQL applications [128].

The selection of environmentally benign additives is equally important because certain conventional cutting fluid additives contain toxic compounds that may adversely affect operator health and the surrounding ecosystem during prolonged machining operations. In contrast, vegetable-oil-based MQL systems largely eliminate hazardous chemical constituents while maintaining excellent lubrication efficiency. Recent investigations consistently demonstrate that biodegradable vegetable oils combined with MQL technology effectively replace conventional mineral-oil-based cutting fluids in machining aluminium alloys, titanium alloys, hardened steels, stainless steels, and other difficult-to-machine materials while substantially reducing environmental and occupational health risks [129–132]. The integration of sustainable lubrication strategies with biodegradable vegetable oils therefore represents one of the most promising approaches for achieving environmentally responsible manufacturing.

Recent advancements in MQL technology have further enhanced the applicability of vegetable oils in precision machining. Ultrasonic-assisted MQL (UMQL), electrostatic MQL (EMQL), and nano-enhanced MQL significantly improve atomization quality, droplet transport, and lubricant penetration into the cutting zone. Enhanced atomization produces finer droplets with greater momentum, allowing the lubricant to reach the tool–chip interface more effectively while minimizing airborne oil mist and lubricant consumption. Consequently, improved lubrication, lower friction coefficients, reduced cutting temperatures, superior chip morphology, and longer tool life have been reported compared with conventional MQL systems.

Hybrid cooling techniques further broaden the applicability of vegetable-oil-based lubricants. For instance, combining vegetable-oil MQL with cryogenic cooling successfully integrates efficient lubrication with intense cooling, thereby overcoming one of the principal limitations of conventional MQL under severe machining conditions. Experimental investigations involving liquid nitrogen-assisted MQL have demonstrated significant reductions in cutting force, tool wear, and surface roughness while substantially increasing tool life during machining of compacted graphite iron and other difficult-to-cut materials. Similarly, tribological studies indicate that cryogenic MQL provides superior cooling capacity without compromising lubrication performance when the lubricant supply strategy is appropriately optimized. The physicochemical properties summarized in Table 4 demonstrate the inherent suitability of vegetable oils as metal cutting fluids. Among these properties, flash point represents one of the most important safety parameters. Vegetable oils generally possess considerably higher flash points than conventional mineral oils [23], allowing their application under elevated cutting temperatures without significant risks of ignition, excessive smoke generation, or fire hazards [35,136]. Consequently, vegetable oils are particularly advantageous in high-speed machining and hard machining applications where thermal loads are substantial.

Another important characteristic is the viscosity index, which indicates the ability of a lubricant to maintain stable viscosity over a broad temperature range. Vegetable oils generally exhibit higher viscosity indices than mineral oils because of their molecular structure. As a result, viscosity decreases more gradually with increasing temperature, allowing the lubricant to maintain a stable lubricating film even under severe thermal conditions [137]. This characteristic contributes directly to lower friction, reduced wear, improved surface finish, and enhanced dimensional accuracy during machining operations.

The density and kinematic viscosity values of most vegetable oils are also comparable with those of conventional mineral and synthetic cutting fluids, enabling their direct application without major modifications to existing lubrication systems. Furthermore, vegetable oils naturally possess relatively high saponification values because of their ester content, eliminating or significantly reducing the need for alkaline additives such as sodium hydroxide that are commonly introduced into mineral-oil-based emulsions to improve emulsification characteristics. Their naturally adequate saponification values facilitate excellent emulsification, stable lubrication, and improved cooling performance while reducing chemical complexity and environmental burden. Consequently, vegetable oils provide satisfactory physicochemical characteristics for direct application as environmentally sustainable MCFs.

Vegetable oils additionally possess relatively high molecular weights and elevated boiling points, resulting in lower evaporation rates and reduced oil mist generation during machining. Reduced volatilization not only improves lubricant utilization efficiency but also minimizes airborne aerosol formation, thereby enhancing operator safety and reducing workplace contamination [138]. Recent studies on advanced atomization techniques further demonstrate that optimized MQL systems significantly decrease particulate emissions while simultaneously improving lubricant penetration into the cutting interface, offering substantial occupational health benefits over conventional flood cooling.

Recent developments in nano-enhanced bio-lubricants have further expanded the capabilities of vegetable-oil-based MQL systems. The incorporation of nanoparticles such as graphite, Al_2O_3, graphene, fullerene (C_{60}), carbon nanodots, and other nanomaterials into biodegradable vegetable oils considerably enhances thermal conductivity, viscosity stability, wettability, and load-carrying capacity. These improvements strengthen the protective tribofilm, reduce frictional resistance, improve heat dissipation, and enhance surface quality. Coconut-oil-based nanofluids containing graphite and Al_2O_3 nanoparticles have demonstrated significant reductions in surface roughness during machining of stainless steel and mild steel, whereas rice bran oil enriched with carbon nanodots exhibits superior thermal conductivity and wettability, leading to enhanced lubrication and lower tool wear. Similarly, C_{60} nanofluid MQL has shown remarkable reductions in cutting force and improved thermal management during titanium alloy machining. Although recent CFD investigations indicate that the improvement in cooling capacity of nano-MQL is relatively modest, the enhanced tribological behaviour and superior boundary lubrication remain the dominant mechanisms responsible for the observed improvements in machining performance. The wide range of biodegradable vegetable oils successfully employed in machining applications is illustrated in Fig. 11**,** whereas their characteristic physicochemical properties are summarized in Table 2**.** Collectively, these properties confirm that vegetable oils provide an excellent balance between lubrication efficiency, thermal stability, biodegradability, operator safety, and environmental compatibility. Although certain limitations related to oxidation stability and low-temperature behaviour remain, these challenges can be effectively mitigated through chemical modification, blending strategies, performance additives, and nano-enhancement technologies. Therefore, vegetable-oil-based MQL systems represent one of the most technically advanced and environmentally sustainable lubrication strategies currently available for modern machining operations. Their continued development through advanced atomization methods, hybrid cryogenic lubrication, and nanotechnology is expected to further improve machining performance while supporting global initiatives toward cleaner production, carbon reduction, and sustainable manufacturing.

8.1. Almond oil, avocado oil, and candlenut oil

Almond oil and avocado oil have attracted considerable attention as environmentally benign vegetable oils because of their favorable physicochemical characteristics, biodegradability, and lubricating capability. Although these oils have been investigated primarily for biomedical, biofuel, and corrosion-protection applications, their inherent tribological properties indicate strong potential for sustainable metal cutting operations under Minimum Quantity Lubrication (MQL). Their renewable origin, excellent biodegradability, and ability to form stable lubricating films make them promising alternatives to petroleum-based cutting fluids, thereby supporting the transition toward environmentally responsible manufacturing practices [174,175].

Almond oil is characterized by its relatively low viscosity, light molecular structure, and superior oxidative stability compared with several conventional vegetable oils. Comparative investigations employing Support Vector Machine (SVM)-based prediction techniques for evaluating the viscosity and density of biodegradable lubricants have demonstrated that almond oil exhibits favorable thermo-physical behavior over a wide operating temperature range. These characteristics contribute to improved atomization, enhanced penetration into the tool–chip interface, and efficient lubrication under MQL conditions while simultaneously minimizing environmental impact through rapid biodegradation [174]. Recent advances in sustainable machining further indicate that vegetable oil-based lubricants possessing optimized viscosity and atomization characteristics improve droplet transport, lubricant infiltration, and tribofilm formation, thereby reducing friction, cutting temperature, and tool wear during machining operations. Such findings reinforce the suitability of low-viscosity bio-lubricants like almond oil for advanced MQL technologies and sustainable manufacturing applications.

In addition to its tribological advantages, almond oil has also demonstrated significant corrosion inhibition capability. One-pot synthesis methods utilizing almond oil as a principal constituent have enabled the development of cost-effective and environmentally benign corrosion inhibitors without requiring complex purification or post-processing stages. Experimental observations confirmed a substantial reduction in corrosion-related material degradation, highlighting the multifunctional role of almond oil as both a lubricant precursor and a protective surface agent [175]. Such dual functionality can be advantageous in machining environments by simultaneously enhancing lubrication performance and reducing corrosion of machined components during storage and handling.

Avocado oil has been extensively investigated as a renewable constituent of biofuel formulations because of its excellent thermal stability and vaporization characteristics. Studies involving preheated biofuel systems reported enhanced combustion efficiency when avocado oil was incorporated as a major component, owing to its ability to promote rapid vaporization before fuel injection [151]. These favorable thermal and flow characteristics suggest that avocado oil can also serve as an effective biodegradable base oil for machining applications. Efficient heat transfer, stable lubricating film formation,

Table 3 Comprehensive analysis of different cooling operations.

Factors	Without Coolants (Dry Machining)	Minimum Quantity Cooling (MQL)	Cryogenic Cooling	High-Pressure Cooling	Bio-Friendly Oil Assisted Cooling
Chip formation and evacuation	Chip formation with neat environment. However, difficulties prevail during chip evacuation.	Poor chip removal and chip breaking.	Chances of chip breakages are prevailing.	Highly efficient in chip breaking. However, difficulties prevail in separating fluids from chips.	Smooth chip removal, but oils tend to stick with chips.
Surface finish	Low level of surface finish.	Good surface finish can be achieved.	Enhanced surface finish.	Enhancement of surface finish.	High possibilities for good surface finish.
Tool life	Tool wears quickly and poor tool life.	Enhanced tool life for the tool.	Prolonged tool life.	Tool wear is a concern.	Prolonged tool life.
Energy conservation	Energy conservation is possible as there is no coolant system.	Low energy requirement due to the absence of pump.	Maximum output in energy consumption.	Energy conservation due to cutting force.	Reduction in cutting force and suitable for higher cutting speed applications.
Energy burdens	High cutting force leads to high energy consumption.	Additional electricity required for the MQL system.	Production of cryogenic consumes energy at a large scale.	Fluid delivery and recycling consume much energy.	Bio-oil production and application need additional energy.
Cost-effectiveness	Cost-effective manufacturing and coolant system setup cost can be eliminated.	Economical cutting fluid usage reduces cost as chip handling cost is cheap.	Cost-effective production.	Overall cost is reduced due to high productivity.	Comparatively costly, but enhanced performance reduces overall cost.
Economic issues	Overall cost increases due to challenging materials which are hard to machine.	Additional cost required for the MQL system.	Setup cost is huge and cryogen consumption is considerable.	Initial investment is high.	Comparatively costlier than other conventional coolants and additional cost required for additives.
Bio-friendliness	Environment-friendly process due to the absence of coolant. Smooth recycling of chips is possible because chips are free from coolants.	Reduced environmental footprint due to minimized water and energy usage.	Elimination of cleaning process at the machining zone.	Environment-friendly benefits through energy conservation, effective coolant recycling, and high productivity.	Swift biodegradation and effectively recyclable.
Environmental issues	Working ambience registers high temperature. More ventilation space is required.	Respiration issues are associated with working environment. Higher chances of particle emission.	Risk involvement due to evaporation of cryogen during delivery.	Negative impacts on the working atmosphere and human health.	Environmental norms can be satisfied. The foaming issue prevails. Lack of corrosion prevention.
Exclusive advantages	Eliminates the requirement of pump/supporting setup.	Low coolant consumption.	Chips are free from coolants such as water, oil, and fluid.	Effective handling of temperature.	Cost-effective coolant disposal.
Exclusive limitations	Heat generation is high. Possibility of weldment between tool and chips.	Complex setup.	Properties vary at interfaces of workpiece and tool.	Higher splattering is experienced.	Possibility of lack of penetration of the fluid.

Similarly, candlenut oil has emerged as another promising renewable lubricant feedstock. Hydrotreated candlenut oil, processed in the presence of suitable catalysts and hydrogen under controlled temperature and pressure conditions followed by distillation, has been shown to produce high-quality bio-lubricants suitable for industrial applications [152]. Hydroprocessing significantly enhances oxidation resistance, thermal stability, and lubricity, thereby overcoming some of the inherent limitations associated with raw vegetable oils. These improvements make hydrotreated candlenut oil a viable candidate for demanding machining environments where lubricant stability and consistent tribological performance are critical.

Collectively, the available literature indicates that although almond, avocado, and candlenut oils have received comparatively less attention than commonly investigated vegetable oils such as neem, coconut, sunflower, and rapeseed oils, their physicochemical properties and renewable nature make them attractive candidates for next-generation biodegradable cutting fluids. Nevertheless, comprehensive investigations focusing on their machining performance under MQL conditions, particularly in turning operations involving difficult-to-machine materials, remain limited. Future research should therefore emphasize comparative machinability evaluation, optimization of atomization characteristics, nanoparticle-enhanced formulations, and long-term tribological performance to establish their industrial feasibility as sustainable alternatives for high-performance MQL systems. [174], [175], [151], [152]

8.2. Castor oil

Castor oil has emerged as one of the most extensively investigated non-edible vegetable oils for sustainable machining because of its excellent lubricity, high film-forming capability, and biodegradability. Owing to its high ricinoleic acid content, castor oil possesses superior viscosity and strong polar molecular structures that promote the formation of a stable lubricating film at the tool–chip interface. These characteristics enable effective friction reduction and wear protection under Minimum Quantity Lubrication (MQL), making castor oil a promising alternative to conventional petroleum-based cutting fluids for environmentally sustainable machining applications [144].

Several machining investigations have demonstrated that the application of castor oil under MQL significantly improves machining performance compared with dry cutting conditions. During the turning of hardened stainless steel, castor oil-based MQL effectively reduced cutting forces, prolonged the service life of carbide-coated cutting tools, and produced superior surface finish. The enhanced machining performance is primarily attributed to improved boundary lubrication and reduced adhesion between the cutting tool and workpiece, resulting in lower frictional heat generation and slower tool wear progression [144,145]. As illustrated in Fig. 13(a), castor oil substantially extends tool life compared with dry machining, while Fig. 13(b) demonstrates a corresponding improvement in surface quality. These observations further confirm that the concentration and stability of biodegradable metal cutting fluids play a critical role in determining the final surface integrity of machined components.

Despite its excellent lubricating capability, castor oil exhibits certain limitations during high-speed machining. Owing to elevated cutting temperatures, rapid evaporation of the lubricant reduces its availability at the cutting interface, thereby diminishing lubrication efficiency under severe machining conditions [145]. To overcome this limitation, hybrid cooling strategies combining castor oil-based MQL with cryogenic cooling have been proposed. The incorporation of nitrogen gas provides efficient heat removal while castor oil maintains effective boundary lubrication, producing a synergistic cooling–lubrication mechanism. Such hybrid approaches considerably increase tool life, reduce thermal damage, and improve surface finish compared with conventional compressed air–oil mist systems, particularly during machining of hardened stainless steels and other difficult-to-machine alloys [176]. Similar conclusions have also been reported in recent investigations on cryogenic MQL and hybrid cooling systems, where the integration of efficient cooling and biodegradable lubrication significantly enhanced tribological performance, reduced tool wear, and improved machining sustainability.

The tribological superiority of castor oil has also been confirmed through comparative evaluations involving various vegetable oils. Owing to its relatively high viscosity and strong lubricating film strength, castor oil consistently exhibits lower friction coefficients and improved surface quality during machining. However, its high viscosity adversely affects atomization characteristics and restricts lubricant penetration into the cutting zone during MQL. To overcome this drawback, researchers have investigated blending castor oil with other vegetable oils in equal proportions to improve flow behavior while preserving its excellent lubricity. Surface profile analyses revealed that castor oil-based blends maintained superior correlation with smoother surface profiles than many other vegetable oil formulations, demonstrating the beneficial balance between viscosity and lubrication performance [177]. Recent studies on sustainable MQL further indicate that optimizing lubricant viscosity and droplet atomization significantly enhances penetration into the tool–chip interface, thereby improving cooling efficiency, tribofilm formation, and machining performance.

Beyond turning operations, castor oil has demonstrated considerable effectiveness in grinding applications. MQL-assisted grinding of nickel-based superalloys using castor oil provided lower specific grinding energy, reduced friction coefficient, improved lubrication, and enhanced overall process efficiency compared with conventional grinding environments [179]. The effectiveness of vegetable oil-based MQL in minimizing energy consumption and improving machining performance is also consistent with recent sustainable machining studies, which reported reductions in tool wear, energy consumption, and surface roughness through optimized eco-friendly lubrication strategies.

Further enhancement of biodegradable lubricants has been achieved through nanoparticle incorporation. In grinding operations, graphene oxide-based lubricants significantly reduced friction coefficient and surface roughness compared with conventional grinding fluids [180]. Likewise, recent nano-MQL investigations have demonstrated that dispersing nanoparticles into biodegradable vegetable oils improves tribological performance by promoting rolling, polishing, and protective film formation at the cutting interface, thereby reducing friction and tool wear while enhancing surface integrity. Although improvements in heat transfer remain relatively modest, the primary benefits arise from enhanced lubrication and stable tribofilm formation rather than cooling alone.

Overall, castor oil represents one of the most promising non-edible vegetable oils for sustainable MQL machining owing to its outstanding lubricity, biodegradability, and wear-reducing capability. Nevertheless, challenges associated with high viscosity, limited atomization, and thermal degradation at elevated cutting temperatures remain significant barriers to its widespread industrial implementation. Future research should therefore focus on viscosity modification through bio-based blending, nanoparticle-enhanced formulations, hybrid cryogenic–MQL systems, and advanced atomization techniques to maximize the machining performance of castor oil while preserving its environmental advantages.

8.3. Groundnut oil, jatropha oil, and karanja oil

Groundnut oil, jatropha oil, and karanja oil have emerged as promising renewable lubricants for sustainable machining owing to their excellent biodegradability, favorable tribological characteristics, and compatibility with Minimum Quantity Lubrication (MQL) systems. Compared with conventional petroleum-based cutting fluids, these vegetable oils offer improved lubrication efficiency, lower environmental impact, and reduced disposal costs while supporting cleaner manufacturing practices. Their abundant fatty acid composition promotes the formation of a stable lubricating film at the tool–chip interface, thereby minimizing friction, cutting temperature, and tool wear during machining operations [146].

Groundnut oil has demonstrated considerable potential as a biodegradable cutting fluid, particularly in the machining of aluminum alloys. Experimental investigations revealed that the application of groundnut oil under MQL substantially reduced cutting forces by approximately 51% while simultaneously suppressing machining-induced tool vibrations [146]. The reduction in vibration is attributed to improved lubrication at the tool–workpiece interface, which minimizes intermittent friction and stabilizes the cutting process. Furthermore, the viscosity of groundnut oil decreases progressively with increasing temperature, enhancing atomization and facilitating lubricant penetration into the cutting zone. Since coolant flow rate directly influences droplet formation and vibration damping, optimization of lubricant delivery becomes essential for achieving superior machining performance. Recent investigations on sustainable MQL systems similarly emphasize that efficient atomization and controlled lubricant transport significantly improve tribological behavior, resulting in lower cutting forces, enhanced surface quality, and improved machining stability.

Among non-edible vegetable oils, jatropha oil has received significant attention because of its excellent lubricity, high biodegradability, and renewable origin. Synthetic ester-based jatropha oil supplied through MQL effectively minimizes cutting fluid consumption while providing sufficient lubrication at the cutting interface, thereby reducing environmental pollution associated with flood cooling systems [157]. The mist-based delivery mechanism ensures efficient utilization of lubricant, minimizes waste generation, and contributes to sustainable manufacturing practices. Experimental studies further indicate that jatropha oil considerably lowers machining energy consumption by reducing frictional resistance between the cutting tool and workpiece. These characteristics make jatropha oil a highly attractive alternative for eco-friendly machining applications involving difficult-to-machine materials.

The tribological performance of jatropha oil can be further enhanced through nanoparticle reinforcement. The incorporation of hexagonal boron nitride (hBN) nanoparticles significantly improves the physicochemical and thermal properties of the lubricant by reducing the coefficient of thermal expansion, increasing thermal stability, and strengthening the lubricating film. The nano-enhanced lubricant exhibits superior anti-wear behavior, lower friction coefficients, and improved load-carrying capacity compared with conventional synthetic ester formulations [157]. Similar observations have been reported in recent nano-MQL investigations, where nanoparticles enhance machining performance primarily through rolling, polishing, and protective tribofilm mechanisms rather than through substantial improvements in cooling capacity. Fullerene (C60), graphene oxide, carbon nanodots, and other nanomaterials have likewise demonstrated significant reductions in cutting force, tool wear, and surface roughness when dispersed in biodegradable vegetable oils under

MQL conditions. Karanja oil is another non-edible vegetable oil that offers considerable potential for sustainable metal cutting applications. Besides its established agricultural value as an organic fertilizer and natural insecticide, karanja oil possesses excellent lubricating characteristics suitable for machining processes. During orthogonal cutting of steel, the application of karanja oil significantly improved chip control by reducing chip thickness and promoting more favorable chip morphology, thereby decreasing cutting resistance and extending tool life [181]. Effective chip breakability also facilitates improved heat dissipation and minimizes tool–chip contact length, ultimately contributing to enhanced machining efficiency and better surface integrity.

To further improve its thermo-oxidative stability, karanja oil has been chemically modified through esterification with trimethylolpropane (TMP) to produce high-performance bio-lubricants. The resulting TMP esters exhibit enhanced thermal stability, improved anti-wear characteristics, lower friction coefficients, and superior oxidation resistance compared with untreated vegetable oil formulations [182]. These improvements enable the lubricant to withstand elevated machining temperatures while maintaining effective boundary lubrication, thereby extending tool life and reducing energy consumption during machining operations. Such chemically modified bio-lubricants represent an important advancement toward industrial implementation of vegetable oil-based MQL systems, particularly for high-speed and high-temperature machining applications.

Overall, groundnut, jatropha, and karanja oils demonstrate significant potential as environmentally sustainable cutting fluids because of their excellent lubricating properties, biodegradability, and compatibility with advanced MQL technologies. Nevertheless, challenges associated with oxidation stability, viscosity optimization, thermal degradation, and long-term storage remain important research concerns. Future investigations should therefore focus on hybrid lubrication strategies, chemically modified bio-lubricants, nanoparticle-enhanced formulations, and intelligent MQL delivery systems to maximize machining performance while maintaining environmental sustainability. Such developments will further strengthen the applicability of non-edible vegetable oils, including neem oil, as next-generation lubricants for sustainable turning and other advanced metal cutting operations.

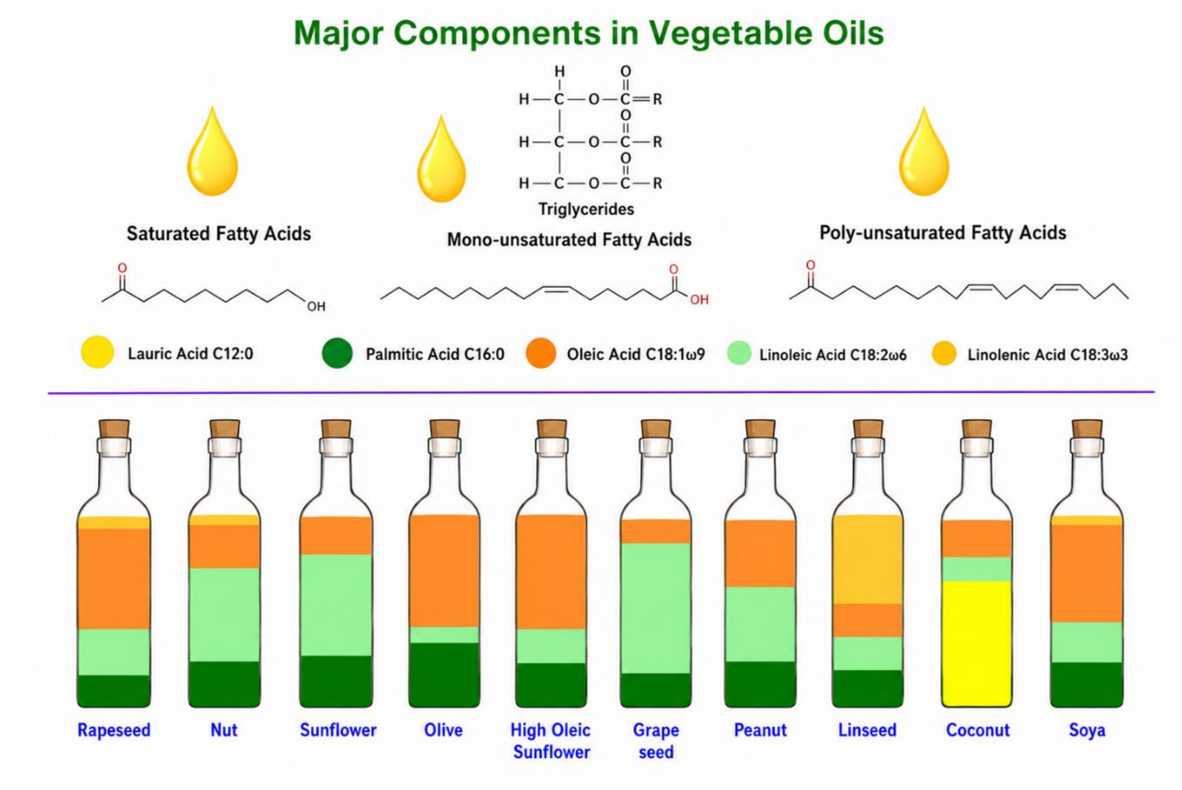

Fig. 11. Major constituents in selected vegetable oils [125]

8.4. Sunflower oil

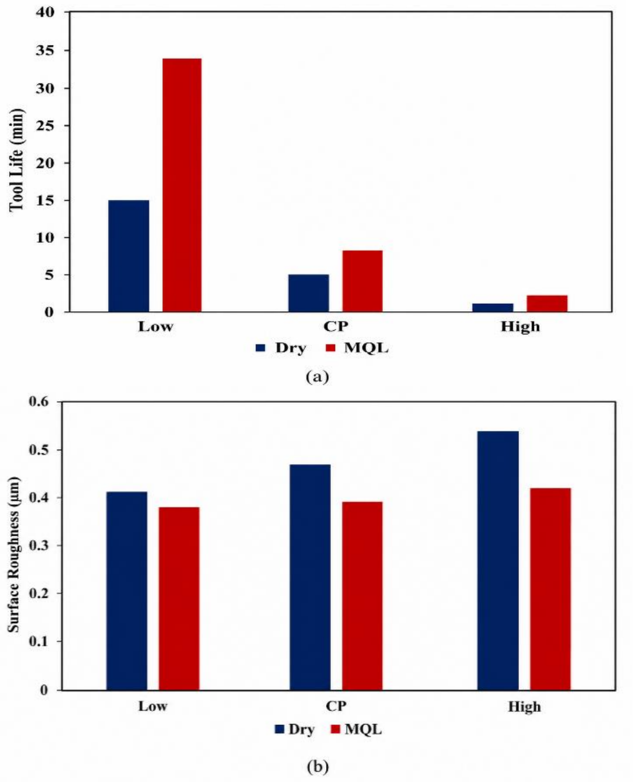

Fig. 12. Tool life and surface roughness performance with respect to cutting speeds for dry and MQL conditions (Source: [134]).

Sunflower oil is one of the most widely investigated biodegradable straight vegetable oils for sustainable machining due to its excellent lubricity, biodegradability, and favorable thermo-physical properties. It can be used in its pure form or blended with additives for both flood cooling and Minimum Quantity Lubrication (MQL) applications. Owing to its high fatty acid content, sunflower oil forms a stable lubricating film at the tool–chip interface, thereby reducing friction, cutting temperature, and tool wear compared with conventional mineral-based cutting fluids [183].

Turning experiments conducted under flood cooling with varying concentrations of extreme-pressure (EP) additives demonstrated that sunflower oil-based metal cutting fluids (MCFs) effectively reduce cutting forces and improve surface finish [183]. The

performance of sunflower oil has been further enhanced by incorporating multi-walled carbon nanotubes (MWCNTs), producing nano-engineered lubricants with superior thermal conductivity, anti-wear behavior, and grinding performance compared with conventional sunflower oil [142]. Similar improvements have been reported for other nano-enhanced vegetable oil-based MQL systems, where nanoparticles primarily improve lubrication through tribofilm formation and rolling mechanisms rather than significantly increasing cooling capacity Comparative studies have shown that sunflower and rapeseed oils outperform mineral oils by producing lower cutting forces and better surface finish during machining [184]. Water–sunflower oil emulsions have also been successfully employed for machining aerospace components, offering an effective balance between cooling and lubrication [185]. Furthermore, sunflower oil-based MCFs reduce spindle thrust force and machining surface roughness compared with commercial mineral cutting fluids, thereby improving machining stability and surface integrity [186].

To enhance oxidation resistance and service life, sunflower oil has been blended with commercial additives that effectively reduce bacterial growth, corrosion, and surface roughness during high-speed machining [34,187]. Overall, sunflower oil is a highly promising biodegradable cutting fluid for sustainable machining. However, improvements in oxidation stability, thermal resistance, and nano-enhanced formulations remain important research directions for expanding its industrial application and provide useful insights for developing high-performance non-edible neem oil-based MQL systems.

8.5. Coconut oil

Coconut oil has gained considerable attention as a biodegradable cutting fluid due to its excellent lubricity, high oxidative stability, and favorable viscosity characteristics. Experimental studies have demonstrated that coconut oil significantly reduces tool wear and surface roughness during steel machining using cemented carbide tools compared with conventional cutting fluids [188]. In hard turning operations, dry machining generally produces higher surface roughness, whereas coconut oil-based lubrication at higher cutting speeds results in superior surface quality and improved machining performance [189,190]. Similar findings from recent sustainable machining studies confirm that vegetable oil-based MQL effectively enhances lubrication, reduces cutting temperature, and improves surface integrity compared with dry machining.

Coconut oil has also demonstrated excellent performance in drilling operations on stainless steel, outperforming other vegetable oils such as sesame, olive, and palm oils because of its superior lubricating ability [191]. Furthermore, the high viscosity index of coconut oil provides remarkable oxidation stability, remaining stable at temperatures up to 294 °C [193]. To improve its applicability, coconut oil has been formulated into stable emulsions using food-grade anionic emulsifiers. Blends of coconut and sesame oils containing approximately 10% emulsifier have shown significant reductions in surface roughness, tool wear, and cutting temperature, making them suitable as environmentally friendly bio-cutting fluids for machining applications [192,194]. These developments highlight coconut oil as a promising renewable lubricant and provide useful insights for developing high-performance non-edible neem oil-based MQL systems.

8.6. Palm oil

Palm oil has emerged as a promising biodegradable lubricant for sustainable machining because of its excellent lubricity, anti-wear properties, and environmental compatibility. During high-speed drilling, palm oil effectively lowers the cutting temperature and reduces thrust force by approximately 11% compared with synthetic cutting oils, thereby improving machining efficiency and tool performance [141]. Furthermore, palm oil-based MQL has been reported to produce better surface quality than synthetic ester lubricants while offering superior friction reduction and wear resistance [140,141].

The performance of palm oil can be further enhanced by incorporating MoS_2 nanoparticles, which improve lubrication, load-carrying capacity, and machining performance under MQL conditions [195]. Similar findings from recent nano-MQL studies indicate that nanoparticles enhance tribological behavior through protective tribofilm formation and rolling mechanisms, leading to lower friction and improved surface integrity.

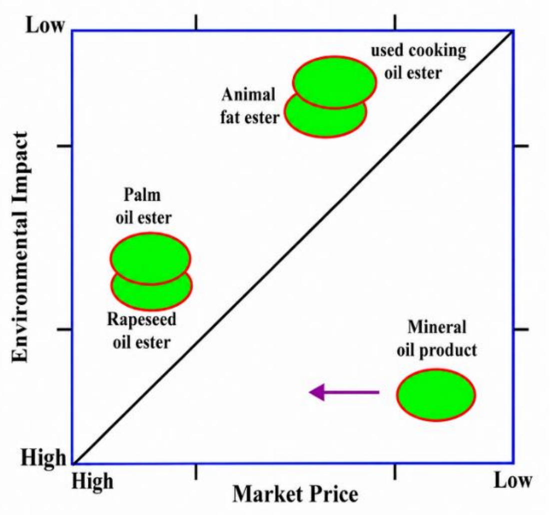

Fig. 13. Economic and environmental performance of palm oil (Adapted from [27]).

Comparative investigations involving palm, soybean, and castor oils suggest that palm oil possesses favorable frictional characteristics suitable for machining applications because of its balanced fatty acid composition [196]. Although palm oil ester exhibits lower environmental impacts than conventional mineral oils, its production cost remains relatively higher, as illustrated in Fig. 14**.** Nevertheless, its biodegradability, excellent anti-wear performance, and compatibility with advanced MQL systems make palm oil a strong candidate for sustainable metal cutting applications.

8.7. Rapeseed oil, soybean oil, and aloe vera oil

Rapeseed and soybean oils are among the most extensively studied biodegradable lubricants for sustainable machining because of their excellent lubricity, biodegradability, and favorable tribological properties. Rapeseed oil has demonstrated effective performance in milling steel, turning under MQL, and machining aluminum–silicon alloys when used alone or blended with synthetic esters, resulting in improved cutting performance and surface quality [197–199]. Comparative studies further confirm that rapeseed oil is completely biodegradable and offers significant environmental advantages over conventional mineral oils [96].

Soybean oil has also shown promising machining performance, particularly when enhanced with MoS_2 nanoparticles. During grinding operations, soybean oil-based nanofluids significantly reduced grinding forces and improved lubrication, with performance comparable to paraffin- and CANMIST-based lubricants [200,201]. Similarly, turning experiments revealed that soybean oil-based cutting fluids produced lower surface roughness and reduced tool wear than petroleum-based metal cutting fluids, confirming their suitability for sustainable machining [19]. Recent nano-MQL studies further demonstrate that nanoparticle-enhanced vegetable oils improve tribological behavior by promoting protective tribofilm formation and reducing friction at the tool–chip interface. In addition to vegetable oils, bio-based additives such as aloe vera gel have also been investigated as eco-friendly lubricant components. Blending aloe vera gel with cottonseed oil significantly improved surface finish during machining by reducing surface roughness under varying cutting conditions [202,203]. Although vegetable oil-based cutting fluids generally involve a higher initial purchase cost than mineral oils, their lower maintenance, recycling, and disposal costs, together with superior biodegradability and compliance with environmental regulations, make them economically and environmentally favorable for long-term industrial applications. Furthermore, large-scale cultivation of oil-producing crops is expected to reduce production costs and enhance the commercial viability of biodegradable cutting fluids.

8.8. Nanofluid oil

The incorporation of nanoparticles into vegetable oil-based cutting fluids has significantly improved the performance of Minimum Quantity Lubrication (MQL) machining. Nanoparticles such as molybdenum disulfide (MoS_2) dispersed in coconut and sesame oils enhance lubrication by reducing friction and improving the load-carrying capacity of the lubricant [204]. The effectiveness of these nanofluids largely depends on selecting nanoparticles with strong intra-layer covalent bonding and weak interlayer forces, which facilitate easy shearing and reduce friction at the tool–chip interface [205].

Coconut oil has shown remarkable performance as a base fluid for nanofluids. The addition of nano-boric acid (50 nm) significantly improved turning performance by lowering cutting forces, friction, and tool wear compared with conventional lubricants [139,206]. Likewise, nanofluids formulated from coconut, canola, and sesame oils under MQL conditions demonstrated substantial reductions in cutting temperature, cutting force, surface roughness, and tool wear owing to enhanced tribological and thermal properties [207]. Recent investigations also confirm that nanoparticle-enhanced vegetable oils improve machining primarily through protective tribofilm formation and rolling mechanisms rather than cooling alone.

Furthermore, hybrid nanofluids, such as Al_2O_3–graphene nanoplatelet (Al_2O_3–GnP) suspensions, have demonstrated superior machining performance by further reducing cutting forces and surface roughness. The concentration of nanoparticles influences the contact angle and wettability of the lubricant, as illustrated in Fig. 15, thereby affecting lubricant penetration and overall machining efficiency [208]. Overall, the integration of nanoparticles with biodegradable vegetable oils represents a promising strategy for developing high-performance, environmentally sustainable metal cutting fluids suitable for advanced machining applications.

8.9. Microstructural comparison of vegetable oils with mineral oils

Microstructural investigations have confirmed that vegetable oil-based cutting fluids provide superior protection against tool wear compared with conventional mineral oils. SEM analysis of uncoated carbide tools after turning AA6061 aluminum alloy revealed that jatropha and pongamia oils mainly produced mild abrasive flank wear, whereas mineral oil caused severe peeling and attrition, indicating greater tool degradation **(**Fig. 16**)** [209]. The superior performance of vegetable oils is attributed to their strong polar molecular structure, which enhances adsorption on metallic surfaces and forms a stable protective tribofilm that reduces friction and wear [195]. Similarly, castor oil develops a dense lubricating film due to its long carbon-chain structure, providing excellent anti-friction and anti-wear characteristics [153].

Tribological studies further demonstrate that jatropha and moringa oils exhibit lower wear rates than mineral oils, with jatropha oil also achieving higher material removal rates during milling of aluminum alloys (Fig. 17 and Fig. 18) [157]. Moreover, SEM and EDX analyses have shown that olive oil-based MQL produces smoother machined surfaces with fewer feed marks and significantly reduces flank wear of tungsten-carbide tools compared with dry machining, thereby extending tool life **(**Fig. 19 and Fig. 20**)** [149]. These observations are consistent with recent studies showing that biodegradable vegetable oil-based MQL enhances tribofilm formation, lowers friction, and improves surface integrity compared with dry and conventional cooling conditions. Although some vegetable oils are more expensive than mineral oils, their superior machining performance, biodegradability, lower disposal costs, and compliance with environmental regulations make them economically attractive for long-term industrial applications. The comparative cost of commonly used vegetable oils is summarized in Fig. 21, while the overall advantages and limitations of vegetable oil-based cutting fluids are presented in Fig. 22**.**

8.10. Improvisation of vegetable oil properties

Despite their excellent lubricating performance and biodegradability, vegetable oil-based cutting fluids possess several inherent limitations that restrict their widespread industrial application. High saturated fatty acid content adversely affects low-temperature flow properties, while unsaturated fatty acids reduce oxidation resistance and thermal stability. In addition, hydrolytic degradation in the presence of moisture can promote corrosion, and poor foaming resistance, seal incompatibility, and filter clogging further limit their long-term performance (Fig. 22) [38]. Nevertheless, recent advancements in sustainable machining indicate that many of these shortcomings can be mitigated through improved lubricant formulations, nanoparticle additives, and advanced MQL delivery techniques, thereby enhancing lubrication efficiency and machining performance.

Several modification techniques have been developed to improve the physicochemical properties of vegetable oils (Fig. 23). These include genetic modification of oilseed crops (e.g., the development of canola from rapeseed), blending different vegetable oils, fractionation, chemical modification through esterification and transesterification, and selective breeding of oilseed crops to obtain desirable fatty acid compositions [210]. Furthermore, the incorporation of environmentally benign additives and nanoparticles has significantly improved oxidation stability, anti-wear performance, and thermal characteristics of bio-lubricants, making them more suitable for demanding machining applications.

Overall, eco-friendly cutting fluids formulated from vegetable oils offer lower cutting forces, excellent biodegradability, reduced environmental pollution, and broader applicability across sustainable machining processes, as summarized in Fig. 24. Continued advancements in bio-lubricant modification and formulation are expected to further accelerate the industrial adoption of vegetable oil-based MQL systems, particularly for non-edible oils such as neem oil.

8.11. The economic and commercial significance of vegetable oils

Vegetable oil-based metal cutting fluids (MCFs) are rapidly emerging as sustainable alternatives to petroleum-based lubricants owing to their biodegradability, renewability, and superior environmental performance. Their global demand is expected to increase steadily, with bio-based MCFs projected to achieve a compound annual growth rate (CAGR) of approximately 3.2%, while vegetable oils are anticipated to capture nearly 30% of the mineral oil market in the coming decades [211,212]. Growing environmental concerns regarding the disposal of conventional cutting fluids, together with increasingly stringent regulations, have accelerated the adoption of vegetable oil-based machining technologies. The expanding market potential of bio-lubricants is reflected in the increasing demand for sustainable MQL systems, as illustrated in Fig. 24.

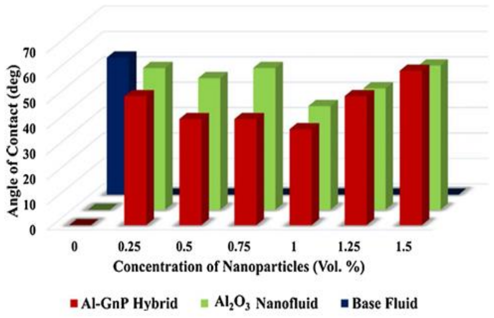

Fig. 14. The angle of Contact observed for different nanoparticle concentration of various nanofluids (Adapted from [198]).

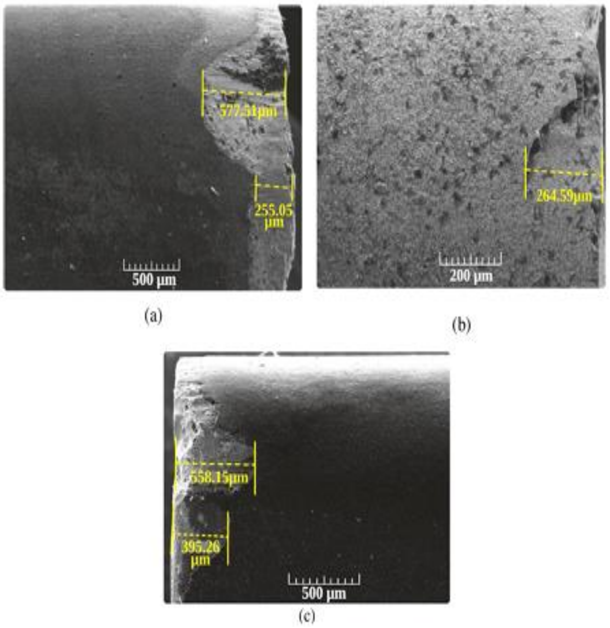

Fig. 15. Microstructural comparison of vegetable oils with mineral oils (Source: [199]).

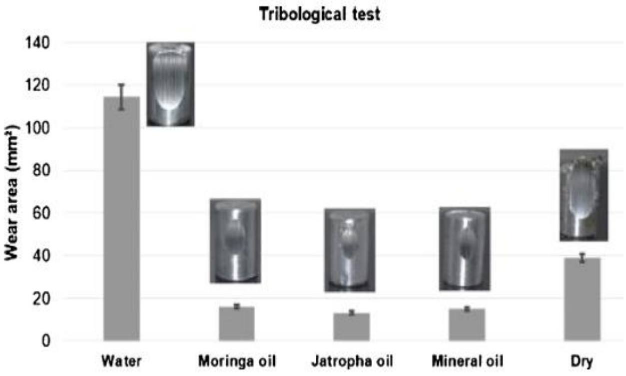

Fig. 16. Wear behaviour of various metal cutting fluids (Source: [216]).

Although vegetable oils generally have a higher initial purchase cost than mineral oils, their long-term economic benefits outweigh this disadvantage. Their complete biodegradability, lower disposal and recycling costs, reduced cutting fluid consumption under MQL, and improved tool life significantly reduce overall machining costs [39]. Recent sustainable machining studies also demonstrate that vegetable oil-based MQL lowers energy consumption, minimizes tool wear, and enhances machining efficiency, thereby improving manufacturing sustainability.

In addition, vegetable oils provide a safer working environment by reducing operator exposure to hazardous chemicals and minimizing environmental pollution. The incorporation of suitable antibacterial additives further suppresses microbial growth, extends cutting fluid service life, and lowers maintenance costs [34,37]. Consequently, vegetable oil-based MCFs offer both economic and environmental advantages, making them a key enabler for sustainable green manufacturing and future high-performance machining applications.

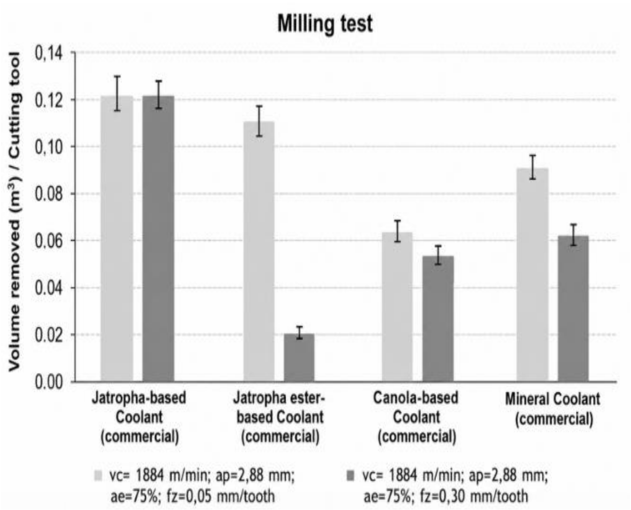

Fig. 17. Material removal in terms of volume with various metal cutting fluid applications (Source: [216]).

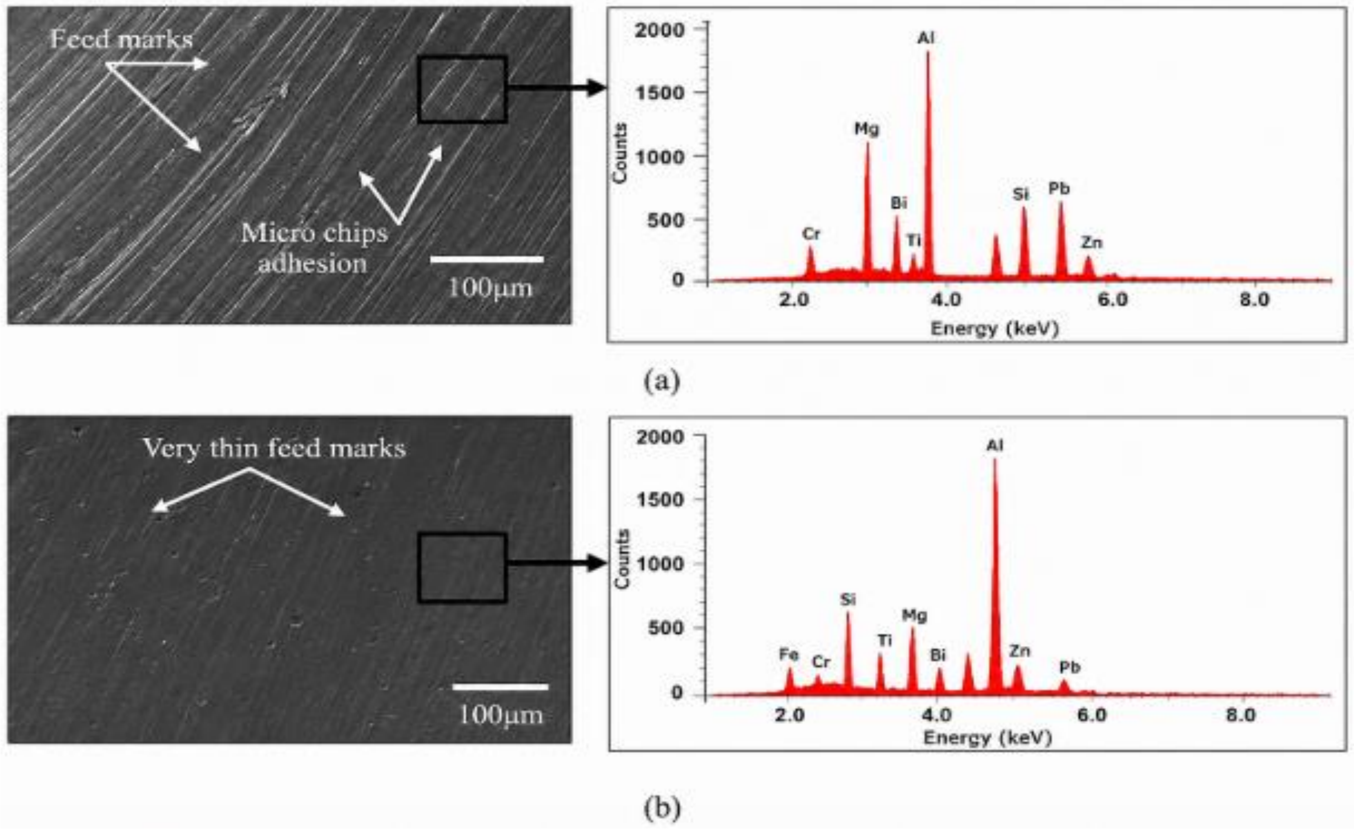

Fig. 18. EDX and respective microstructures of machined surface (a) Dry machining (b) Olive oil-based Minimum Quantity Lubrication (MQL).

9. Open issues, research challenges and future directions

Researchers face many challenges to impart sustainability concerns in using vegetable oils as cutting fluids for machining applications. In this section, we summarize some of the most important challenges related to the mentioned domain, some promising solutions, and future research directions. Table 4 summarizes some key challenges to a successful deployment of Vegetable oil-based cutting fluid for machining tasks along with potential solutions and future research directions.

9.1. Research challenges for imparting sustainability of cutting fluids

I. Although mineral and synthetic oils continue to dominate the metal cutting fluid (MCF) market, increasing environmental concerns and stringent regulations have accelerated the transition toward biodegradable vegetable oil-based lubricants. Studies have reported lower greenhouse gas emissions, including carbon dioxide, methane, and nitrous oxide, when rapeseed and palm oils are used instead of conventional mineral oils [125]. Consequently, developing high-performance bio-based MCFs has become a major research focus for sustainable manufacturing.

II. Vegetable oils possess excellent biodegradability, renewability, and lubricating characteristics, making them promising alternatives to petroleum-based cutting fluids. Several vegetable oils, particularly rapeseed oil, exhibit biodegradation rates approaching 100%, thereby reducing environmental pollution and simplifying recycling and disposal. Their rapid biodegradation supports cleaner and more sustainable machining practices [96].

III. Besides environmental advantages, vegetable oils improve workplace safety by minimizing operator exposure to toxic chemicals and reducing soil, water, and air contamination. Certain vegetable oils, such as almond oil, also exhibit natural corrosion-inhibiting properties, enhancing both machining performance and component protection while maintaining an eco-friendly working environment [174,175].

IV**.** Among the various vegetable oils, castor oil has demonstrated excellent performance in turning hardened stainless steel by extending tool life and reducing friction, although its rapid evaporation at high cutting speeds limits its application under conventional MQL. The performance of jatropha oil can be further enhanced by incorporating hexagonal boron nitride (hBN**)** nanoparticles, resulting in improved wear resistance, friction reduction, heat transfer, and lubrication. Recent nano-MQL studies consistently confirm that nanoparticle-enhanced vegetable oils significantly improve tribological performance and machining efficiency.

V**.** Vegetable oils such as sunflower, palm, coconut, and soybean have consistently demonstrated superior machining performance by reducing thrust force, improving surface finish, lowering tool wear, and enhancing lubrication compared with conventional mineral oils. These findings reinforce the potential of vegetable oil-based MQL systems as sustainable and high-performance alternatives for future metal cutting applications, including non-edible neem oil-based machining.

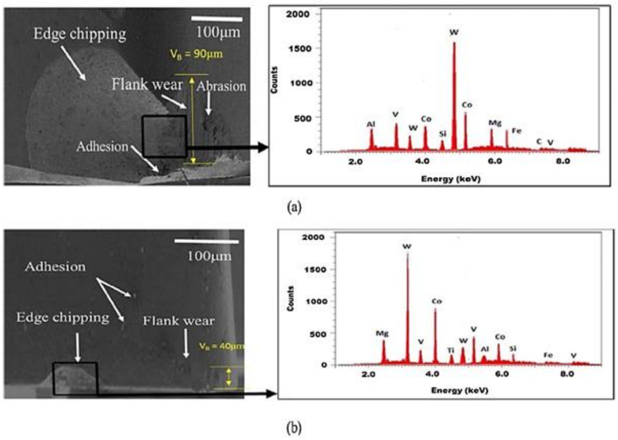

Fig. 19. EDX and respective microstructures of insert wear (a) Dry machining (b) Olive oil-based Minimum Quantity Lubrication (MQL).

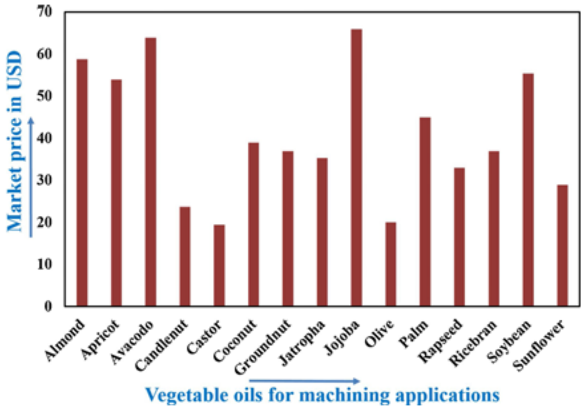

Fig. 20. Cost comparison of vegetable oils used for the machining applications in USD.

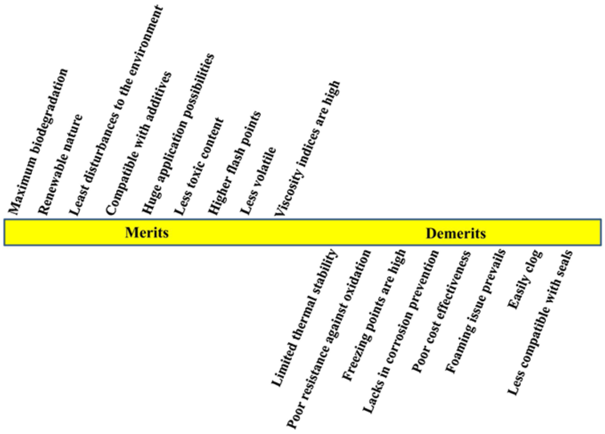

Fig. 21. Merits and demerits of vegetable oils (Image is drawn based on the theory from [13,28,10]).

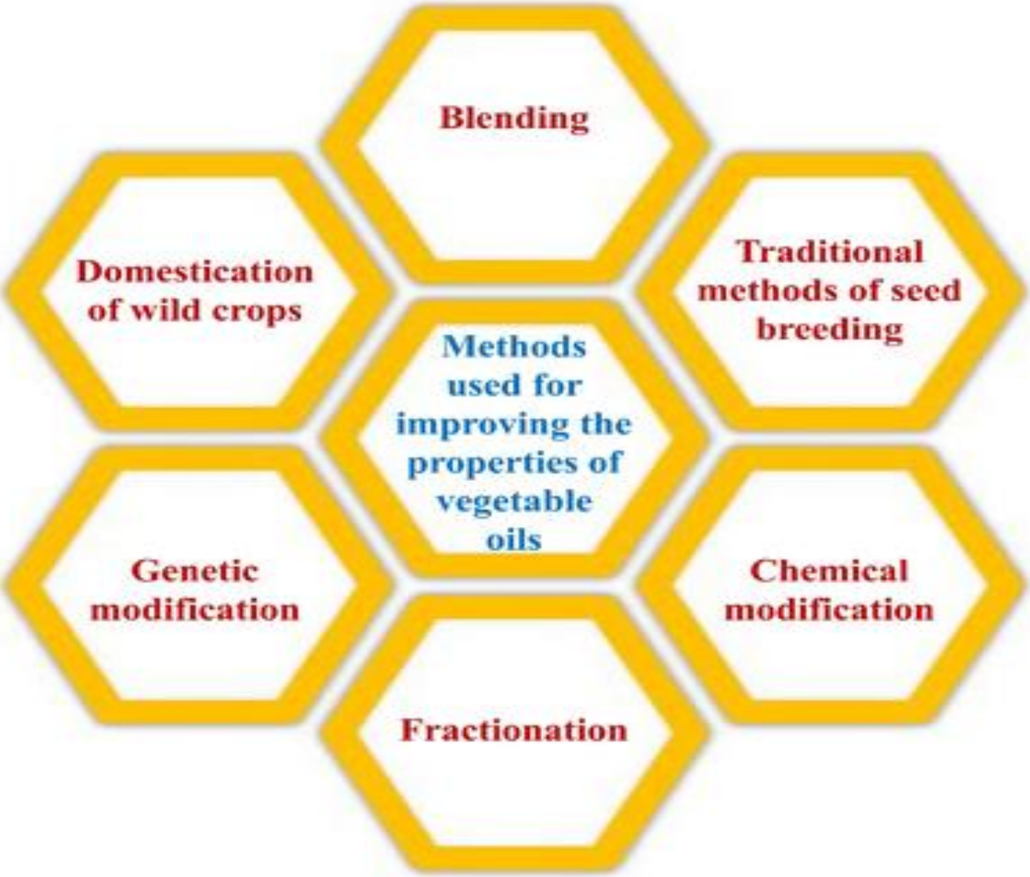

Fig. 22. Methods used for enhancing the properties of vegetable oils (Image is drawn based on the theory from [28,10].

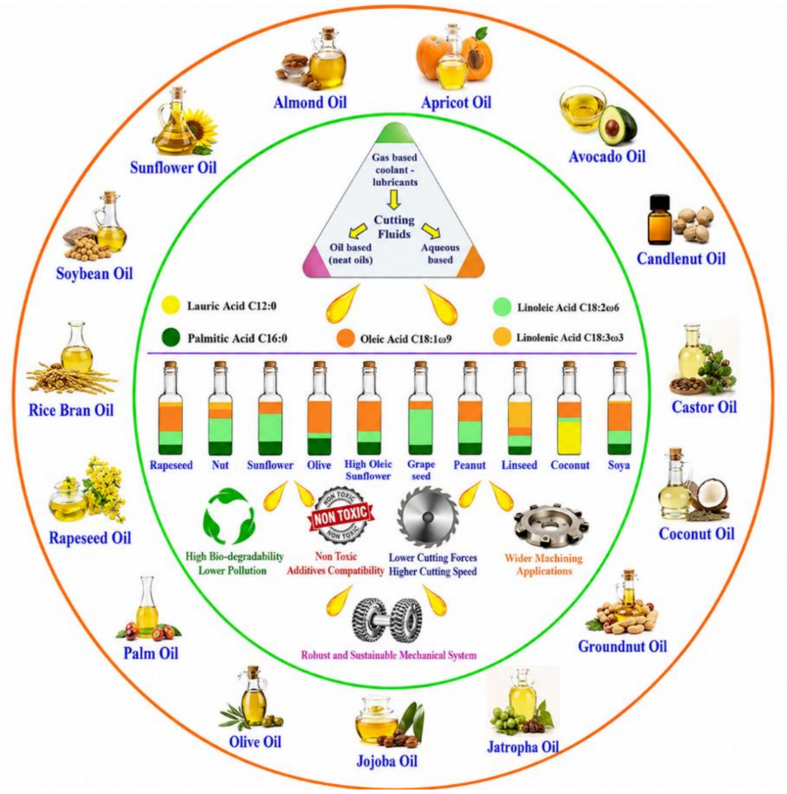

Fig. 23. Significance of bio-friendly fluids.[10]

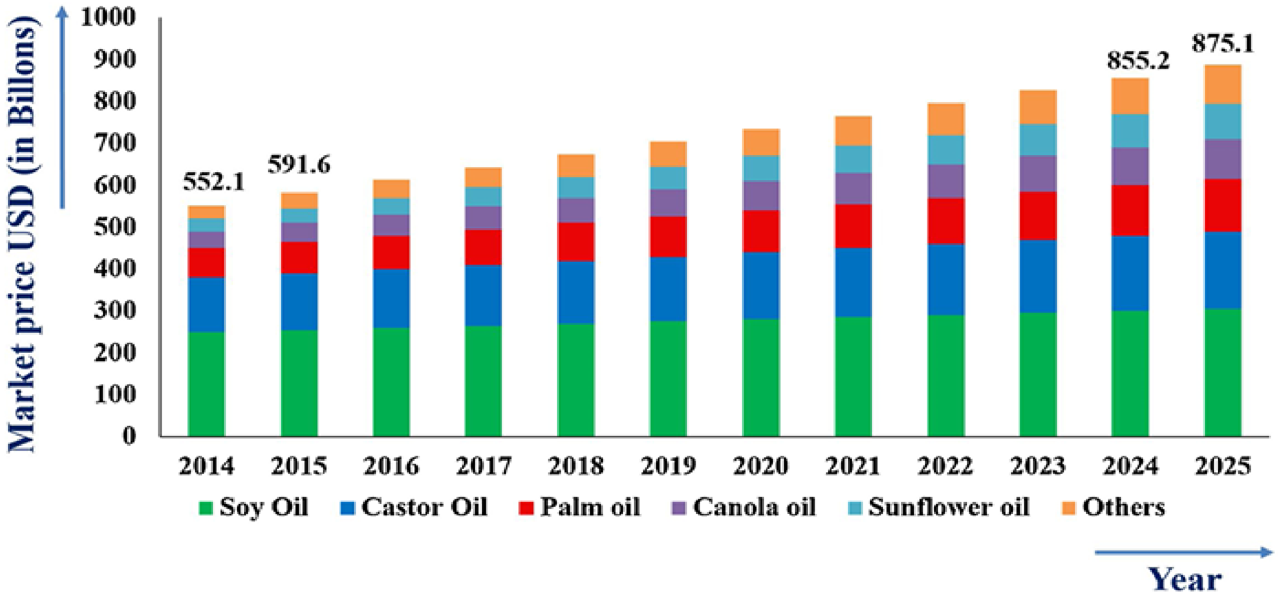

Fig. 24. Market share of various vegetable oils in the United States (US) in Billions (US Dollars) [211,10].

Table 4 Vegetable oil-based cutting fluid in machining applications, challenges, potential solutions and future research directions.

Challenges	**Issues**	**Potential impact of vegetable oil- based machining applications**	**Future research directions of vegetable oils for machining tasks**
Adaptation of Bio- friendly cutting fluids	Emission of CO and methane	Industrial labs and research fraternities are working on environment- friendly cutting fluids to suppress emission of unwanted chemicals.	Full-fledged adaptation of bio-friendly vegetable oils as cutting fluids
Sustainability	Swift biodegradation	Biodegradation and the recyclable nature of vegetable oils ensure cleaner and sustainable manufacturing platforms	Usage of nanoparticles as additives, ionic liquids, and blended oils to understand the efficacy
Healthy atmosphere	Corrosion resistance	Ensures natural corrosion inhibition property along with the non-pollutant air, water and soil.	Oil-miscible ionic liquids with anti-corrosion properties also could support superior corrosion reduction.
Physicochemical properties	Friction restriction	Have superior wear and friction properties with the inclusion of nanoparticles	Enhancing flash point, saponification value, viscosity index provides more flexibility
Superior surface finish	Thrust force	With minimum thrust force, superior finishing of tools could be guaranteed	Oil with lowest coefficient of friction and best surface quality for better machining results.
Contamination	Fire and Smoke-related risks	Registration of least contamination are integral feature of most vegetable oils and helps to reduces risks of fire and smokes	Enhancement of thermal as well as oxidative stability.

Turning operation	Flank wear	Nano-boric acid blended with coconut oil provides superior turning property of machining processes and reduces flank wears.	Pressurized-oil jet assisted hard turning
Tool Lifespan	Hardened tool	Palm oil extends the lifespan of tools with reduced trust forces on hard steel tools.	Cryogenic liquid nitrogen assisted machining
Minimum quantity lubrication	Flash point, Molecular weight and boiling point	Helps to extend the vaporization time and control the mist formation, that provides positive sign towards machining applications	Minimum quantity lubrication are to dominate conventional wet cooling process.
High Speed drilling applications	Super alloys	Usage of palm oil as the coolant provides positive inferences with better product realization on titanium alloys at high speed drilling.	Non-ferrous materials and super-alloys
Dry machining applications	Eco-friendly cutting	Proper utilization of vegetable oils have been given much significance in providing eco-friendly solutions compared to dry machining	Composite - coated tools with Titanium alloy variants
Product quality	Production enhancement	Directly influences the product quality with reduced cutting force on steel materials.	Efficacious handling of the aging effect of vegetable oils
Economic hurdles	Market scope	Large scale deployment of cutting processes, significantly reduces the impact of economic issues	Nano fluid form of vegetable oils reduces machining costs and sustains cutting fluid stability
Commercialization	Bio-friendly fluids.	Impact of Nanoscience and tribology properties could be exploited for mass applications and sustainable production	Hybrid the machining approaches to harvest multiple benefits.

VI. Although dry machining eliminates cutting fluids, its limitations in cooling, lubrication, and surface quality make vegetable oil-based MQL a more practical and sustainable alternative for difficult-to-machine materials. Recent advancements such as ultrasonic-assisted MQL, nano-MQL, and hybrid cooling strategies have further expanded the applicability of vegetable oil-based lubricants.

VII. Despite their superior environmental performance, commercialization of vegetable oil-based cutting fluids remains challenging because of higher initial costs, oxidation stability, and large-scale production limitations. However, lower disposal costs, improved operator safety, regulatory compliance, and advances in chemical modification and nanotechnology are expected to accelerate their industrial adoption.

VIII. Overall, vegetable oils possess the essential physicochemical, tribological, and environmental characteristics required for next-generation metal cutting fluids. Further research on non-edible oils, nano-enhanced bio-lubricants, hybrid MQL technologies, and large-scale commercialization will strengthen their role in sustainable machining, particularly for high-performance turning operations using neem oil-based MQL systems.

9.2. Future research directions outlook

1. Sustainability and Economic Assessment: Future studies should focus on the large-scale adoption of vegetable oil-based MCFs by evaluating not only their machining performance but also their long-term economic, environmental, and sustainability

benefits through comprehensive life-cycle assessment (LCA).

2. Health and Environmental Impact**:** More quantitative investigations are required to assess the reduction in occupational health risks and environmental pollution achieved by replacing conventional cutting fluids with biodegradable vegetable oils, thereby establishing their economic advantages.

3.Application to Advanced Materials**:** Most current studies are limited to ferrous materials. Future research should explore the performance of vegetable oil-based MQL in machining non-ferrous alloys, titanium alloys, nickel-based superalloys, and advanced composites, which are increasingly used in aerospace and automotive industries.

4. Advanced MQL and Hybrid Cooling**:** Further research should focus on combining vegetable oils with nano-MQL, ultrasonic-assisted MQL, cryogenic-MQL, and hybrid cooling techniques to improve lubrication, cooling efficiency, and machinability of difficult-to-machine materials. Recent studies have demonstrated significant potential for these advanced lubrication strategies.

5. Nanoparticle-Enhanced Bio-lubricants**:** Optimization of nanoparticle type, concentration, dispersion stability, and long-term performance remains an important research area for improving the tribological and thermal properties of vegetable oil-based nanofluids.

6. Chemical Modification of Vegetable Oils**:** Improving oxidation stability, thermal stability, viscosity index, and storage life through chemical modification and bio-based additives will enhance the industrial applicability of vegetable oil lubricants.

7. Commercialization and Industrial Implementation**:** Future work should address lubricant stability, maintenance, cost-effectiveness, and large-scale manufacturing challenges to accelerate commercialization of biodegradable cutting fluids.

8. Fundamental Tribological Studies**:** More multidisciplinary investigations on the interactions between vegetable oil-based lubricants, cutting tools, and workpiece materials are required to better understand tribofilm formation, wear mechanisms, and lubricant degradation under actual machining conditions.

10. Conclusion

Metal cutting fluids account for nearly **16–30%** of the total machining cost, with disposal expenses often exceeding the initial purchase cost. Although mineral and synthetic oils are relatively inexpensive to procure, their high maintenance, disposal costs, and stringent environmental regulations have accelerated the search for sustainable alternatives. Consequently, biodegradable vegetable oil-based cutting fluids have emerged as promising solutions for green manufacturing.

The major findings of this review can be summarized as follows:

- **V**egetable oil-based MCFs are environmentally friendly, biodegradable, and offer a sustainable alternative to conventional mineral oils.
- Their excellent lubricity and strong surface adsorption capability enable the formation of protective tribofilms, reducing friction, cutting temperature, tool wear, and improving surface finish during machining.
- The favorable physicochemical properties of vegetable oils, including high viscosity index, high flash point, and renewable nature, make them suitable for various machining applications.
- Recent developments in nano-enhanced vegetable oils, hybrid cooling strategies, and advanced MQL techniques have further improved machining performance by enhancing lubrication, wear resistance, and heat dissipation.
- A comprehensive understanding of different cooling and lubrication techniques is essential for selecting the most suitable eco-friendly machining strategy for specific materials and cutting conditions.
- Although challenges related to oxidation stability, thermal stability, and commercialization remain, continued research on bio-lubricant modification and non-edible vegetable oils, particularly neem oil, is expected to further expand their industrial application and support sustainable machining practices.

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