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A Review On The Application Of Bio-Oils As Sustainable Cutting Fluids In Machining Operations

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Abstract: With growing concern for the environment and stricter rules on using petroleum-based cutting fluids, there's been a strong push toward finding cleaner and safer alternatives in machining. Bio-oils made from plants, used cooking oil, and animal fats are standing out as promising options—they're less toxic, break down more easily in the environment, and offer great lubrication. This paper reviews how these bio-oils are being used in machining processes. It takes a closer look at their impact on overall machining performance also examines how enhancing bio-oils with nanoparticles or modifying them chemically can boost their effectiveness for industrial use. Comparative studies show that, in some cases, bio-oils can match or even outperform traditional fluids. Still, challenges like how well they hold up over time, how they're stored, and their cost need to be addressed. Overall, this review highlights the growing role of bio-oils in making manufacturing cleaner and more sustainable.

***Index Terms* - ,** WCO, sustainability, machining, bio-oils, cutting fluids, lubrication.

I. INTRODUCTION

Fluids used in cutting serve to for the dissipation of heat, lowering of friction, and removal of shavings as well as serving as one of the more vital components while machining a part. This also leads to improvement of the finishing and quality of the final product. In addition, cutting fluids prolong the tool life and boost overall performance. However, most of the current cutting fluids available are petroleum-based and have grave environmental and health hazards. Usually, the fluids are toxic and non-biodegradable and challenging to dispose of safely. Also, the fluids pose a risk to the exposed people working in the machinery. With these in mind, and the growing cost of oil, there is a critical need to identify safer and environmentally compatible alternatives. One such is bio-oil that complies with the requirements and offers a potential solution is waste cooking oil (WCO). It is an oil that is readily available in the form of spent oil in houses and restaurants. Usually thrown away, WCO can instead be reused as a cutting fluid. This saves money, reduces waste, and conserves the environment. WCO has excellent lubrication and is biodegradable. Experiments indicate that, when properly processed, it matches or even surpasses the performance of mineral oils during machining. With its adoption, it also supports the concept of a circular economy—converting waste into something valuable. With this, WCO is now a clever and sustainable choice for application in machining processes.

I. Classification of Cutting Fluids

Cutting fluids are a critical part of machining processes because they enable heat dissipation, reduce friction, and extend tool life. Cutting fluids are divided into four primary categories: straight oils, soluble oils, semi-synthetic fluids, and synthetic fluids, as indicated in table 1. Each of these is designed uniquely and offers distinct benefits depending on the machining process. For example, certain fluids are designed to cool, while others are designed to provide better lubrication. The following table gives a concise description of these types, including their composition, primary characteristics, and typical applications.

Table 1: Classifications of cutting fluids used in machining operations:

Classification	Base Composition	Characteristics	Applications
Straight Oils	Pure mineral or vegetable oils	Excellent lubrication, poor cooling	Low-speed operations, tapping, reaming
Soluble Oils	Oil + water emulsion	Good lubrication and cooling	General-purpose machining
Semi-Synthetic Fluids	Oil + water + synthetic compounds	Balanced cooling and lubrication	Moderate to high-speed machining
Synthetic Fluids	Water-based, no oil content	Excellent cooling, minimal lubrication	High-speed operations, grinding

II. Bio-Oils as Cutting Fluids

Bio-oils are the oils of natural origin that may be applied as cutting fluids in machining. They are derived from various sources such as vegetable oils (coconut or sunflower oil), restaurant and domestic used cooking oils, and plant oils of non-food origins such as jatropha or neem. Bio-oils possess natural chemicals which mitigate heat and friction when cutting. On account of this, tools are protected and cutting is smoothed. Bio-oils are safe for the environment and disintegrate naturally, so they don't create pollution like standard cutting oils. Waste cooking oil use also saves waste and money. Because they are plant-based, they are easily replaced and won't be depleted, like fossil fuels. In general, bio-oils are a solid, earth-friendly option for machining use.

III. Physicochemical Properties of Bio-Oils

The chemical and physical properties of bio-oils are most crucial to how effective they are as cutting fluids. Their properties such as thickness, flash point, and ability to resist decomposition assist in lubrication and cooling during machining. Their natural tendency to resist rusting guards against tool and material damage. Also, their decomposability in nature and minimal harm to health make bio-oils a safer, better alternative for the environment and the individuals who use them.

1. Viscosity refers to how thick or thin the oil is. For cutting fluids, the right viscosity of the oil is that the oil flows well and supports the cutting tool, reducing friction and wear during machining. The viscosity of a cutting fluid matters for machining because it determines how well the fluid can cool and lubricate the cutting area. When the viscosity is right, the fluid creates a protective film between the tool and workpiece, reducing friction, prevents heat from building up, and prolongs the life of the cutting tool. This also improves the surface quality and keeps sizes accurate in the final product. If the fluid's viscosity is too low (too thin), it may not provide enough lubrication and cooling, causing too much wear on the tool and overheating. If it's too high (too thick), the fluid may struggle to flow into tight spaces or remove heat and chips efficiently. That's why choosing a cutting fluid with the right viscosity for machining is very important for smooth, efficient, and high-quality machining. Table 2 below shows some typical cutting fluids used in machining and their usual viscosity ranges.

Table 2: Cutting fluids used in machining operations along with their typical viscosity ranges

Type of Cutting Fluid	Description	Typical Viscosity (cSt @ 40°C)
Straight Oils	Mineral or synthetic oils used without dilution; excellent lubrication	20 – 100+
Soluble Oils (Emulsions)	Oil-in-water emulsions; good cooling and moderate lubrication	2 – 10
Semi-synthetic Fluids	Blend of synthetic and soluble oil characteristics; balanced cooling/lubrication	2 – 6
Synthetic Fluids	Water-based with no oil; excellent cooling, minimal lubrication	1 – 3

2. The flash point is the exact temperature when the oil becomes flammable, and the pour point is the lowest temperature when the oil will still pour. A cutting fluid with a high flash point and low pour point is safest to use and functions best over a broad temperature range...
3. Oxidative stability refers to the ability of oil to withstand air exposure and high temperatures. Stable oils do not degrade easily, leading to longer life and improved performance in machining operations.
4. Corrosion resistance is essential for preventing tools and workpieces from rusting. It prevents damage to the machines and keeps the finished products in good condition
5. Biodegradability means the oil can break down naturally without harming the environment, and low toxicity makes it safer for the people handling it every day.

These characteristics render bio-oils eco-friendly and safer for application in manufacturing processes

IV. REFINING AND MODIFICATION TECHNIQUES

These techniques helps to improve their performance as cutting fluids. Additives make them work better, while nano-enhanced oils offer even greater benefits like better heat control and longer-lasting performance.

Filtration, Neutralization, and Esterification

1. Filtration takes away the dirt, impurities, and particles in bio-oil, making it purer and safer to utilize in cutting. It keeps the machine from clogging and also shields it
2. Neutralization process eliminates the acidic contents of the bio-oil, enhancing its stability and performance. It keeps the oil in use longer and performs better while machining.
3. Esterification improves the thickness and heat resistance of the oil by reacting with bio-oils and alcohols. This makes it a more effective cutting fluid for smoother machining.
4. Additives are blended into bio-oils to enhance their performance during machining. These include:

- *Antioxidants prevent the oil from breaking down when subjected to heat.*
- *Anti-wear agents Minimize friction and wear on tools, increasing tool life.*
- *Corrosion inhibitors shield the tools and workpieces from rust.*
- *Surfactants and emulsifiers enhance the oil's lubricating and cooling properties for easier machining.*
- *Nano-enriched bio-oils have smaller nanoparticles that enhance their characteristics:*
- *Nanoparticles enhance the oil's heat dissipation quickly such as Al_2O_3, SiC*
- *Nanoparticles form a silky layer on tools to minimize friction such as CNTs, GO, ZnO*
- *Nanoparticles aid in improving surface finish and lowering tool wear, enhancing the efficiency of machining processes such as GO, Silver nanoparticles*

V. CHARACTERIZATION TECHNIQUES

1. FTIR (Fourier Transform Infrared Spectroscopy)

FTIR is an analytical use of spectrometry focused on finding the material composition of an object and its constituents. The sample is placed on the beam of the infrared light (Figure 1 shows this), wherein the chemical bonds absorb specific wavelengths of light. The pattern of absorption resulting from this shows as peaks on a spectrum that gives information pertaining to the type of chemical group present, whether esters, alcohols, or carboxyl. In the case of bio-oils, FTIR is used to examine their chemical composition as well as to make any process adjustment or adjustment to the sample during refining or alteration. It verifies that the oil has desired properties and maintains stability and function when used as a cutting oil.

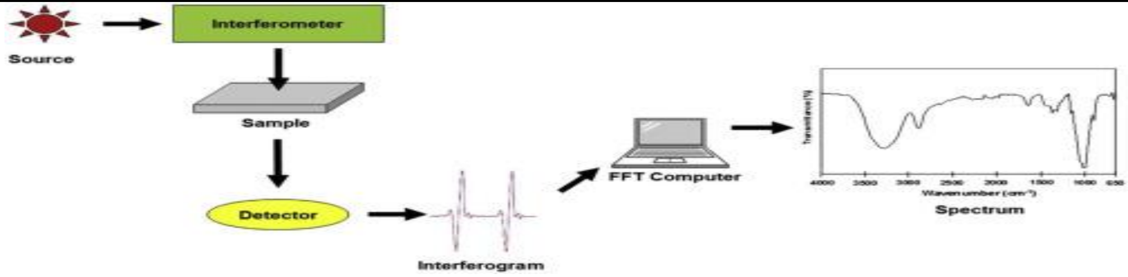

Figure 1: Fourier Transform Infrared Spectrometer [1]

2. TGA (Thermogravimetric Analysis)

As depicted in Figure 2, TGA (Thermogravimetric Analysis) is the procedure used to identify a specimen's weight change concerning time as the specimen is gradually heated. This method enables determination of a materials' stability by evaluating its weight loss with increase in temperature. This technique is essential in defining when and how a material undergoes physical change in weight due to heating. When bio-oils are employed as cutting fluids, TGA becomes important for ascertaining their stability under thermal stress that occurs during machining. This test will illustrate if the oil can withstand increased temperature without degrading or evaporating during use. In this test, several milligrams of oil is placed on the pan of balances in the furnace and all weight changes will be continuously recorded during heating constantly.

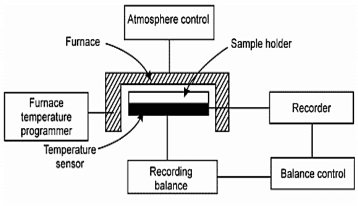

Figure 2: Thermogravimetric Analysis

3. GC-MS (Gas Chromatography-Mass Spectrometry)

C-MS as indicated in figure 3 is a two-stage method applied to separate and analyze compounds in a sample. Gas chromatography (GC) first separates the sample into its components according to their volatility. Mass spectrometry (MS) next determines the molecular structure of each component by detecting the mass-to-charge ratio of its ions. GC-MS is applied to determine the chemical composition of bio-oils, particularly to detect the presence of certain compounds such as fatty acids, esters, and other reactive materials.

It assures the bio-oils' purity and decides whether they can be used as a cutting fluid or not. The sample is evaporated and transported by an inert gas within a column. While the components are separating, they travel into the mass spectrometer, where they are characterized by their mass spectra.

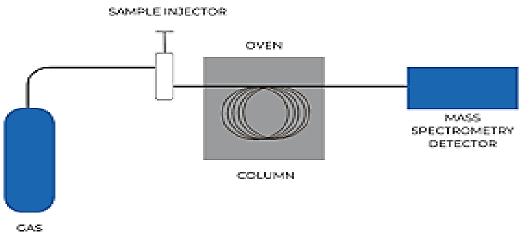

Figure 3: Gas Chromatography-Mass Spectrometry [2]

4. Tribological Testing Methods

Tribology is the science that deals with friction, lubrication, and wears between surfaces that come into contact with each other. The bio-oil's effectiveness as a cutting fluid in minimizing friction and wear during machining processes can be assessed using tribological test procedures. Such tests are usually aimed at measuring the surface roughness, coefficient of friction, and the wear rate. This rough data is crucial with respects to whether a bio-oil will stand valid in terms of its cutting tool and workpiece protection during the machining operations. The development of effective cutting processes is possible through tribological testing which improves tools by reducing friction and wear and enhancing durability. In a standard test configuration, a tool and workpiece are set to rotate against one another at a specific controlled pressure and speed. Friction and wear data is captured using weight or sensor-based mechanisms.

VI. Performance Evaluation in Machining Operations

7.1 Lubrication and Cooling Effects

Sankaranarayanan [3]. carried out a thorough survey on the application of vegetable oils as cutting fluids in machining operations, highlighting their role in advocating green and sustainable manufacturing. The investigation starts by presenting the pollution and health risks posed by traditional mineral oil-based cutting fluids, including dermal irritation, toxic fumes, and contamination. The authors critically assess a series of vegetable oils such as sunflower, coconut, castor, and jatropha, describing their physicochemical characteristics, degradability, and machining performance. The review illustrates from the detailed figures and comparison tables how the addition of compatible additives improves the lubricating characteristics, thermal stability, and tool life as evident in figure 4 below. The authors don't miss out on the deficiencies of vegetable oils, mentioning their poor oxidation stability, high viscosity, and restricted cooling capacity, which need adjustment through formulation approaches. Also, different cooling technologies—dry, MQL, cryogenic, high-pressure, and bio-oil assisted cooling—are contrasted based on energy efficiency, surface finish, tool wear, and cost. The review is evenly weighted between technical, environmental, and economic factors, presenting a comprehensive analysis of vegetable oil-based metal cutting fluids (MCFs). In the end, the research places these bio-based fluids not only as environmentally friendly substitutes, but as competitive, high-performance contenders for machining operations in the future.

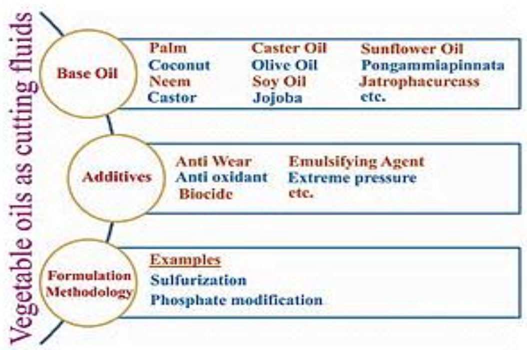

Figure 4: Vegetable oils as MCFs

Ojolo [4] investigated the performance of straight vegetable oils such as groundnut, coconut, palm kernel, and shea butter as cutting fluids during turning of aluminum, copper, and mild steel in cylindrical form. Primary intention of this work was to observe whether these bio-oils are able to lower cutting forces and enhance machining efficiency in a more environmentally friendly manner. The results indicated that groundnut oil was particularly effective in minimizing cutting force during turning aluminum, especially at a cutting speed of 8.25 m/min. Palm kernel oil worked best on copper at low feed rates. Coconut oil, however, resulted in higher cutting forces on all materials and was therefore less effective as a lubricant. The performance of the oils was found to be different for different materials being machined. For the case of mild steel, the variation between the oils was less dramatic, although shea butter had a slight edge in reducing friction. The research further observed how cutting force tends to decline with higher speeds in aluminum and copper but not for mild steel, possibly due to built-up edge effects and strain hardening. The excellent performance of certain oils was attributed to their molecular composition—in particular, their elevated viscosity and polarity, which contribute to the formation of a thick pressure-resistant film of lubrication. Generally, the research is in favor of the utilization of some bio-oils as sustainable and efficient substitutes for traditional cutting fluids in machining.

Arun [5] explored the transition from conventional cutting fluids to more sustainable, bio-based alternatives in the manufacturing sector. The review outlines the significant health and environmental hazards associated with mineral and synthetic oils, which remain widely used in industry—citing issues such as pollution, respiratory ailments, and toxicity. As a sustainable solution, the study focuses on bio-based cutting fluids (BCFs), particularly vegetable oils, due to their biodegradability, renewability, and superior lubricating properties. Oils like castor, palm, and groundnut demonstrate favorable characteristics such as high viscosity and flash points, though limitations like low oxidation stability and thermal conductivity persist. To address these drawbacks, the review discusses the integration of additives and nano-enhancements. A key insight from the study is the potential of Minimum Quantity Lubrication (MQL), which significantly reduces fluid consumption while improving tool life and machining efficiency. The combination of BCFs with MQL and nanotechnology is presented as a promising strategy for achieving green, cost-effective machining.

Additionally, the review emphasizes improved workplace safety through reduced chemical exposure. Overall, the study strongly advocates for the adoption of BCFs as both an environmentally responsible and industrially viable choice.

Review paper by Debnath [6] addresses the growing need for environmentally friendly practices in machining, with a focus on cutting fluids and their application. The authors highlight the increasing demand for renewable and biodegradable cutting fluids to mitigate the environmental concerns and regulations associated with traditional, mineral-based cutting fluids. The paper emphasizes the critical role of cutting fluids in machining processes, noting their influence on heat generation, surface quality, and tool wear. Effective application of cutting fluids is essential for reducing heat at the cutting zone and improving surface roughness, which are key indicators of product quality. The review covers the development and performance of bio-based cutting fluids, particularly vegetable oils, as promising alternatives to mineral-based fluids, citing their potential to reduce ecological problems.

In addition to cutting fluid types, the authors discuss cleaner application techniques, including dry cutting, minimum quantity lubrication (MQL), and cryogenic cooling. These methods aim to minimize the amount of cutting fluid used while maintaining or enhancing cutting performance. The review also touches on the challenges and advancements in the field, such as the development of nano-lubricants to improve lubrication and reduce friction in machining. Overall, the paper provides a relevant overview of the shift towards sustainable machining practices, with a focus on cutting fluids and cooling techniques.

7.2 Influence on cutting force and temperature

Gajrani [7] investigate the effectiveness of an eco-friendly bio-cutting fluid (BCF) in hard machining of AISI H-13 steel, comparing it to mineral oil (MO) under both flood cooling (FC) and minimum quantity cutting fluid (MQCF) conditions. The research highlights the environmental concerns associated with traditional mineral oil-based cutting fluids and explores the potential of BCF as a sustainable substitute. A key aspect of the study is the use of an in-house designed MQCF system, which delivers a fine mist of cutting fluid to the cutting zone, minimizing fluid consumption. The authors compare the biodegradability, physical properties, and machining performance of BCF and MO and optimize MQCF parameters. The study reveals that BCF offers better biodegradability and lubrication than MO. Notably, the MQCF technique, especially with BCF, significantly reduces cutting force, feed force, friction coefficient, and surface roughness. The findings support the use of BCF and MQCF as promising strategies for sustainable hard machining.

Gani [8] conducted an experimental study on the influence of vegetable-based cutting fluids on surface roughness in shaping operations. The research explored the potential of rice bran oil, almond oil, and sunflower oil to improve surface finish when machining mild steel, stainless steel, and EN 8. The study acknowledges the benefits of cutting fluids in machining, including increased tool life, reduced thermal deformation, enhanced surface smoothness, and effective chip removal from the cutting zone. The machining parameters considered in the experiments were speed, feed rate, and depth of cut. Surface roughness values were measured after machining the three materials under various conditions.

The findings of the research indicate that vegetable oil-based cutting fluids possess strong lubricating abilities and are environmentally friendly. The study suggests that cutting fluids like sunflower oil can effectively minimize friction and temperature in the cutting zone. Overall, the paper contributes valuable insights into the comparative performance of different vegetable-based cutting fluids in shaping operations.

Kazeem [9] explores the advancing use of vegetable-oil-based cutting fluids in sustainable machining operations. The authors address the rising interest in eco-friendly lubricants due to growing environmental and health concerns. Vegetable oils are highlighted as a promising alternative to mineral-oil-based cutting fluids because of their renewability, biodegradability, and good lubricating properties.

The paper comprehensively reviews the various vegetable oils used as cutting fluids for machining different engineering materials. It critically analyzes the effects of vegetable oils on cutting force, surface finish, tool wear, and cutting area temperature. The review shows that vegetable-oil-based cutting fluids meet cleaner manufacturing standards and can perform as well as or better than mineral-oil-based cutting fluids. The authors discuss the application of vegetable oils in turning, grinding, drilling, and milling operations. They present findings from various studies on the impact of vegetable-oil-based cutting fluids on surface roughness, tool life, cutting forces, and tool wear.

Kazeem [10] explored the development of bio-cutting fluid from watermelon oil and assessed its performance in machining AISI 1525 steel. The study addresses the growing interest in vegetable oil-based cutting fluids as a substitute for traditional mineral oils due to the latter's negative environmental and health effects. The authors investigated the use of watermelon oil, a lesser-known vegetable oil, to reduce the competition between edible oils and industrial applications. The research compared watermelon oil to mineral oil in turning AISI 1525 steel, focusing on cutting temperature, surface roughness, and chip formation mode. A Taguchi experimental design with Grey Relational Analysis was used to analyze parameter effects and optimize cutting parameters. The results indicated that watermelon oil can perform comparably to mineral oil, with optimal cutting parameters identified for both fluids.

7.3– Surface roughness and tool wear

Radhika [11] investigated using bio-oils as lubricants in turning. They highlighted that cutting fluids are important for reducing friction and improving product quality in machining. But, using mineral oil in turning can be harmful to human health and the working environment. To find safer alternatives, they studied machining mild steel with gingelly oil as a lubricant. They compared the results with dry cutting and using petroleum-based lubrication. Their findings as tabulated in the table 3, showed that gingelly oil helps reduce cutting force and create a smoother surface finish compared to dry cutting

Table 3: cutting force, surface roughness and chip reduction coefficient for the different processes

	Dry Cutting Process	Petroleum Based Lubrication	GingellyOil Lubrication
Cutting Force (in N)	301	278	247
Surface Roughness (in µm)	1.18	1.12	0.92
Chip reduction coefficient	3.5	3.22	2.98

Study by Jyothi [12] explores the potential of bio-oils as cutting fluids in drilling mild steel, addressing the growing need to replace harmful petroleum-based fluids in machining. The research emphasizes that while cutting fluids are essential for easing the machining process and prolonging tool life, traditional options pose significant threats to both the environment and operator health. The authors specifically investigate the influence of vegetable oil-based cutting fluids on chip formation and tool wear, two critical factors in drilling operations. The paper details the methodology employed to conduct drilling experiments using bio-oils, analyzing the resulting chip morphology and tool wear patterns. The findings highlight the potential of vegetable oils to serve as effective and sustainable alternatives to conventional cutting fluids, offering a pathway to reduce the environmental impact of machining processes. This research contributes valuable insights into the tribological performance of bio-oils in drilling, providing a foundation for further optimization and industrial adoption of these eco-friendly lubricants.

Onuoha [13] studied the impact of cutting fluids on surface roughness when turning AISI 1330 alloy steel. The authors used the Taguchi method, a statistical approach, to design their experiments and analyze the results. Experiments were conducted on a manually operated lathe, with each test repeated three times using a fresh high-speed steel (HSS) cutting tool to ensure accurate surface roughness measurements. The Taguchi L27 orthogonal array was employed to efficiently study the effects of various cutting parameters. The research focused on understanding how different cutting fluids affect the smoothness of the machined surface, a critical factor in manufacturing quality. The authors used signal-to-noise (S/N) ratio and analysis of variance (ANOVA) to determine the optimal cutting conditions and identify the most influential parameters. Their findings contribute to optimizing turning processes for AISI 1330 steel, providing valuable insights for improving machining outcomes in industries that utilize this material. The study highlights the effectiveness of the Taguchi method in analyzing and optimizing machining parameters.

VIII. Comparison with Conventional Cutting Fluids

Bio-oils, especially from waste cooking oil (WCO), are a promising alternative to traditional cutting fluids. They help improve tool life by minimizing wear and offer better surface finish due to their natural lubricating ability. Though conventional fluids are known for heat control, refined bio-oils can also manage machining temperatures effectively. Bio-oils are cheaper, especially when made from waste, and are easily available. They are safer for workers as they are non-toxic and produce fewer harmful fumes. Being biodegradable, they are also less harmful to the environment. Using bio-oils reduces the need for petroleum-based products. Overall, they support eco-friendly and cost-effective machining.

IX. Challenges and Limitations

Using waste cooking oil (WCO) as a cutting fluid has some limitations that need to be addressed. It can break down due to oxidation and high temperatures during machining. The availability and quality of WCO are not always consistent, which can affect performance. Bio-oils are also prone to microbial growth during storage, reducing their shelf life. To improve their stability and effectiveness, special additives are often needed, which adds to the complexity of formulation. These challenges must be managed for safe and efficient use in machining [14].

X. Scope for Future Research

1. Implementation in real-time industrial applications
2. Use of advanced sustainability metrics (LCA, carbon footprint)

XI. Conclusion

Bio-oils are a sustainable and environmentally friendly option compared to traditional cutting fluids, thanks to their biodegradability and low toxicity.
Waste cooking oil (WCO) stands out as a practical and affordable bio-oil source that can be effectively reused in machining after proper treatment.
Refining methods and the use of additives—especially nanoparticles—significantly boost the performance, stability, and lubrication quality of bio-oils.
Research shows that bio-oils help reduce tool wear, improve surface finish, and manage heat during machining, performing well under real conditions.
To make bio-oils more viable for industry, challenges like oxidation, storage issues, and inconsistent quality need to be addressed through further research.

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