JURNAL TEKNIK MESIN (JOURNAL OF MECHANICAL ENGINEERING)
VOL. 15, NO. 01, February 2026
https://publikasi.mercubuana.ac.id/index.php/jtm/index
DOI :10.22441/jtm.v15i1.36830

A Review : the Effect of Nanoparticles in Vegetable Oil on Surface Roughness in Machining Processes

Ayu Pratiwi[1], Alfian Noviyanto[1]
Mechanical Engineering Departement, Faculty of Engineering, Mercu Buana University Jakarta, 11650, Indonesia

E-mail: 011189ayupratiwi@gmail.com

Abstract--*The use of mineral oil-based and synthetic coolants in machining processes remains dominant, despite their negative impacts on the environment and occupational health. Vegetable oils have emerged as an environmentally friendly alternative due to their biodegradability, non-toxicity, and renewable sources. However, thermal and tribological limitations restrict their performance under extreme conditions. To address this, various studies have investigated the addition of nanoparticles to vegetable oils to form nanofluids with improved lubrication and cooling performance. Nanoparticles such as aluminum oxide (Al_2O_3), molybdenum disulfide (MoS_2), and graphene have been shown to enhance thermal conductivity, reduce friction, and form protective tribological layers. This literature review discusses the effect of combining vegetable oil with nanoparticles on surface roughness in machining processes. The review is conducted through systematic literature tracing, selection, and critical analysis of relevant publications. The results show that nanofluids can significantly reduce surface roughness, particularly in Minimum Quantity Lubrication (MQL) systems. The effectiveness of nanofluids is strongly influenced by nanoparticle type, size, and concentration, with optimal concentrations varying but remaining within a specific range (e.g., 2.5% for Al_2O_3). This study emphasizes that the development of plant-based nanofluids is a strategic approach toward efficient, environmentally friendly, and sustainable machining.*

Article History:
Received: November 03, 2025
Revised: January 08, 2026
Accepted: January 09, 2026
Published: January 28, 2026
Keywords: *Surface roughness, nanoparticles, nanofluids, vegetable oil*

1. INTRODUCTION

Coolants in the machining process act as lubricants, extending the service life of cutting tools, improving machining efficiency, and producing better surface quality [1]. Currently, more than half of the coolants used are still mineral-based or synthetic [2], [3]. The use of such lubricants has negative environmental impacts, particularly due to the disposal of non-environmentally friendly waste, toxic properties, and their inability to degrade naturally in the environment. This situation has driven increased demand for metalworking fluids (MWFs) or environmentally friendly coolants that are readily biodegradable [4].

An MWF is considered environmentally friendly primarily by its level of biodegradability, the ability of a liquid to be broken down by microorganisms. In this context, vegetable oil becomes a promising alternative because it has a biodegradability rate of up to 95%, thereby reducing the potential for environmental pollution [5].

The potential of vegetable oils is now seen as an excellent alternative to replace petroleum-based lubricants in industrial applications, particularly as metalworking fluids (MWF). Their main advantages include their environmentally friendly characteristics, their derivation from renewable sources, low toxicity levels, and high biodegradability [6].

Currently, various Research efforts are focused on developing bio-based cutting fluids from a variety of vegetable oils that are abundantly available in different regions around the world. These oils are being explored not only to replace conventional lubricants but also to enhance machining performance through more efficient and environmentally friendly formulations. This proves that vegetable oil as a base material for MWF is not only an ecological choice but also a strategic direction aligned with the development of a sustainable manufacturing industry.

Although vegetable oils are superior in terms of environmental impact and tribology, several challenges remain, such as thermal degradation at high temperatures and lubrication stability under heavy loads. To overcome these limitations, new approaches combining vegetable oils with nanoparticles have been developed, yielding nanofluids that offer improved cooling and lubrication capabilities. Nanoparticles such as aluminum oxide [7], cellulose [8], and molybdenum disulfide [9] serve as additive lubricants due to their ability to fill micro-gaps on surfaces and form a protective nano-layer. This capability can reduce friction and wear and improve the surface quality of machined parts [10].

Although many studies have examined the use of vegetable oils and nanoparticles separately or in combination, a comprehensive study is still needed to examine their relationship with surface roughness in machining processes, particularly across different particle types and sizes.

Against this background, this study is conducted as a systematic literature review to examine and compare previous Research focusing on the use of vegetable oils and nanoparticles in machining processes. The primary focus is directed toward the effect of their combination on the surface roughness of the processed materials. This Research is expected to provide both theoretical and practical insights for the development of environmentally friendly and sustainable machining technology, as well as serve as a reference for future experimental Research and the development of working fluids.

2. METHODOLOGY

This study uses a literature review approach, tracing, sorting, and critically analyzing various scientific publications on the effects of vegetable coolants and nanoparticles on surface roughness in machining processes, including turning, milling, and drilling. A literature search was conducted across leading journal databases and relevant documents, prioritizing quantitative, experimental studies that measure surface roughness parameters in machining processes. Articles were selected based on topic relevance, clarity of methodology, and the measurability of results, and then reviewed narratively to identify common patterns, performance comparisons among fluid types and nanoparticles, and their impact on the quality of machining outcomes. This approach enabled the author to develop a deep, critical synthesis of knowledge, serving as a foundation for scientific understanding and practical recommendations in sustainable machining technology.

3. COOLANT IN MACHINING PROCESSES

In the machining process, one important aspect that affects quality is the use of coolant, which serves as a lubricant, coolant, and cleaner for the cutting area. Generally, coolants used are divided into three main categories: mineral-based fluids, synthetic fluids, and vegetable oil-based fluids. In general, these three types of fluids reduce friction and excessive heat generated by the interaction between the cutting tool and the workpiece, extend the life of the cutting tool, and improve the surface quality of the machined part.

3.1 Synthetic Coolant

Synthetic coolants are fluids that do not contain mineral oil and are entirely based on water-soluble chemicals, such as surfactants, corrosion inhibitors, and lubricating additives [11]. This type is generally used as a clear solution, providing better visibility of the cutting process. Its cooling capacity is very high due to water's high thermal conductivity, while its lubricating effect comes from special additives containing phosphorus or chlorine.

Synthetic fluids exhibit optimal performance in mist-cooling processes for S45C steel, with lower surface roughness than mineral fluids [12]. However, these fluids have limitations in lubricity and can cause skin irritation if not appropriately managed. According to previous Research, synthetic fluids tend to be more chemically stable and are suitable for use in flood or MQL systems with high pressure [13].

3.2 Mineral Coolant

Mineral-based coolants are petroleum distillates combined with various protective and lubricating additives. This type is a conventional cutting fluid that has long been used in the metal industry, especially for heavy machining processes such as rough turning or drilling hard metals [14].

According to a study, the use of mineral fluids results in higher surface roughness than synthetic or vegetable fluids on S45C steel [12]. This is due to its lower cooling ability, although its lubricating power is suitable for high-pressure processes. Environmentally, this fluid poses problems because it is not readily biodegradable and produces hazardous waste, requiring specialized disposal and treatment systems [15].

3.3 Vegetable Coolant

Vegetable coolants are an increasingly popular, environmentally friendly alternative. These coolants are derived from biological sources such as coconut oil, palm oil, canola oil, or soybean oil. Their natural ester content and high polarity provide superior lubrication properties, even compared to mineral oils [4]. Other studies also mention that vegetable-based oils perform better than other cooling fluids [53].In MQL systems, vegetable oils can form a strong protective film between the cutting tool and the workpiece, reducing friction and wear.

The use of palm oil and jatropha in the MQL method can significantly reduce surface roughness and cutting forces, especially in the machining of stainless steel and aluminum [4], [16]. In addition to their good tribological performance, vegetable oils are also biodegradable and environmentally friendly [1]. However, this liquid has limitations in terms of thermal stability and shelf life, especially when continuously exposed to high temperatures. Therefore, recent Research has focused on chemical modification or the addition of nanoparticles to improve its stability [17].

Table 1. Comparison of Machining Process Performance and Surface Quality

Fluid Type	Fluid Sub-type	Machining Process	Ra (μm)	Performance	Reference
Syntetic	Semi-synthetic (SUN Cut ECO-33)	Turnig	0.24	35% better than the dry process	[18]
	Semi-synthetic (water + phosphate ester + inhibitor)	Milling	0.77	7.22% better than fully synthetic	[2]
Mineral	Straight oil (without water, high viscosity)	Turning	0.88	Ra of Palm Oil 0.48 μm	[3]
	Soluble oil (oil + water, 5–10% emulsion)	Turning	2.49	21.20% better than mineral base oil	[4]
Vegetable	Palm Oil	Turning	1.78	49.02% better than the dry process	[5]
	Coconut Oil	Turning	1.91	39.56% better than mineral base oil	[4]
	Cottonseed oil	Milling	0.15	16.30% better than the dry process	[6]
	Sunflower Oil	Drilling	2.312	27.75% better than distilled water	[7]

Table 1 shows a comparison of the performance of several types of cutting fluids—including synthetic, mineral, and vegetable fluids on the surface roughness (Ra) parameters resulting from the machining process. In general, the Ra value is used as an indicator of the final surface quality of the workpiece, where the smaller the Ra value, the smoother and better the machined surface.

Among synthetic fluids, SUN Cut ECO-33, an environmentally friendly semi-synthetic fluid, delivered the best results with an Ra value of 0.24 μm in the turning process. This achievement was 35% better than dry machining, underscoring the important role of lubrication in improving final surface quality. Another water-based semi-synthetic formulation containing phosphate esters and inhibitors also demonstrated exemplary performance in milling processes, achieving an Ra value of 0.77 μm and a 7.22% improvement in quality compared to fully synthetic fluids.

Meanwhile, mineral-based cutting fluids showed poor to low performance. Straight oil with high viscosity produced a Ra of 0.88 μm, which is still acceptable but not as good as that of palm oil reported in other studies. The use of soluble oil (a water-in-oil emulsion at 5–10%) produced the highest Ra value in this group, at 2.49 μm. However, the results were 21.20% better than those with conventional mineral-based oil.

The vegetable oil group shows great potential as an environmentally friendly alternative to lubricants. Palm oil in the turning process on carbon steel produced an Ra of 1.78 μm, with a 49.02% improvement in surface quality compared to the dry process. Meanwhile, coconut oil produced a Ra of 1.91 μm, representing a 39.56% improvement over mineral oil. On the other hand, cottonseed oil demonstrated excellent performance in the milling process, achieving a Ra of only 0.15 μm and outperforming certain synthetic fluids by 16.30%. Although sunflower oil showed a high Ra (2.312 μm) during drilling, it was still 27.75% better than distilled water.

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In general, the results of this table indicate that modern semi-synthetic fluids remain the best choice for producing a very smooth surface. However, certain types of vegetable oils (such as cottonseed oil) are beginning to show competitive performance, even surpassing mineral fluids and approaching or matching synthetics under certain conditions. On the other hand, mineral fluids exhibit relatively suboptimal performance and raise concerns regarding environmental impact and occupational health.

These findings are in line with the latest Research trends that encourage the application of green machining, a machining process that is not only technically efficient but also ecologically sustainable [23]. The use of vegetable oils as cutting fluids can be a strategic answer to the needs of modern industries that prioritize performance, cost efficiency, and environmental responsibility.

4. NANOPARTICLES IN VEGETABLE COOLANTS

Vegetable oils, such as coconut oil, palm oil, sunflower oil, and cottonseed oil, are known to have natural lubricating properties, high biodegradability, and low toxicity [24]. However, the main limitation of vegetable lubricants is their low thermal stability and heat conductivity, which hinder their ability to withstand high temperatures in the cutting zone [4]. To overcome this shortcoming, an innovative approach has been adopted by adding nanoparticles as multifunctional additives to improve fluid performance significantly.

Nanoparticles are tiny particles, typically less than 100 nanometers in size [25]. As a result, nanoparticles exhibit physical and chemical properties distinct from those of the same material in conventional sizes. In vegetable coolants, nanoparticles are used to improve the fluid's performance by enhancing its ability to absorb and conduct heat, reduce friction, and withstand high pressure and heavy machining conditions [26].

There are several types of nanoparticles used for vegetable coolant mixtures. The most common are metal oxide nanoparticles such as aluminum oxide (Al_2O_3) [27], silver (Ag) [28], and copper (Cu) [29]. In addition, there are non-metallic nanoparticles, such as silicon dioxide (SiO_2) and graphene [30]. Each has its own advantages. Aluminum oxide, for example, is very stable at high temperatures, making it suitable for use in extreme-temperature machining processes [27]. Copper oxide has excellent heat conductivity, making it ideal for cooling cutting areas [29]. Meanwhile, graphene is known for its exceptional strength and smoothness, enabling it to provide excellent lubrication effects and reduce wear on cutting tools [31], [32].

By adding nanoparticles to vegetable coolants, we can create much more efficient and effective coolants. The combination of natural ingredients derived from vegetable oils and the power of nanoparticle technology creates a practical, environmentally friendly solution [33]. This is a concrete step towards a greener, safer, and more sustainable machining industry [6]. When these nanoparticles are mixed into vegetable oils, heat transfer efficiency in the cutting zone increases significantly. This is because the nanoparticles act as a thermal bridge between the oil and the metal surface, accelerating the heat conduction process and reducing the accumulation of heat that can damage cutting tools [34]. For example, adding Cu to cutting fluids in specific percentages has been shown to reduce cutting temperatures by 20–30% compared to conventional lubricants [29]. Additionally, nanoparticles function as tribological layer-forming agents on working surfaces. Their tiny size allows them to fill micro-gaps on the metal surface, forming a protective film that prevents wear and significantly reduces friction [34].

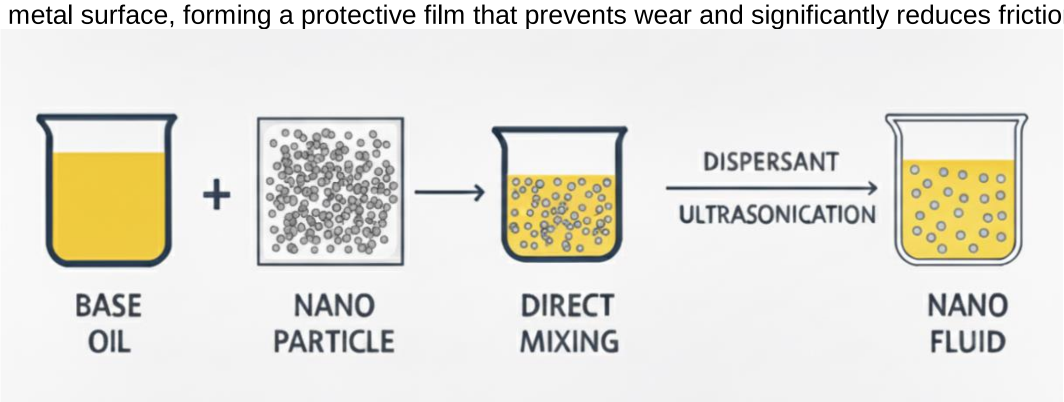

Figure 1: Two Stages of Nonfluid Production

Mixing nanoparticles with a cooling fluid produces a new product called a nanofluid [34]. The mixing process is shown in Figure 1. Usually, the mixing of base oil and nanoparticles is performed using magnetic stirring to achieve homogeneous mixing [35]. Nanoparticles in cooling fluid often clump and settle due to the attractive forces between particles. To prevent this, additives called dispersants and ultrasonic vibrations are used to keep the particles evenly distributed. The main challenge in nanofluid production is maintaining particle stability and preventing settling. Nanofluid dispersibility refers to the ability of nanoparticles to remain dispersed in the fluid without settling due to their own weight [34].

Cutting efficiency, which affects surface quality, does not always increase with higher nanoparticle concentrations in the coolant; it tends to decrease at specific concentrations [36], [37]. For example, in a turning process using Al_2O_3 nanoparticles with palm oil at concentrations between 0.5% and 5%. The optimal concentration was 2.5% Al_2O_3 particles, which exhibited the smallest contact angle, the lowest surface tension, and the largest wetting area. When the particle concentration exceeded 3%, improvements in strength, thermal conductivity, and viscosity began to decrease [38]. Additionally, shear stress is significantly influenced by the concentration of the mixture between the fluid and nanoparticles [39]. Therefore, the issue of optimal nanofluid concentration has become a widely researched topic. Previous studies investigating nanoparticle concentration in coolant fluids are shown in Table 2.

Table 2. Several Studies on the Concentration of Nanoparticles in Turning Processes

Vegetable oil	*Nanoparticles*	*Percentage*	*Evaluation*	*Reference*
Castor Oil	hBN	0.05% wt	- Cutting Zone Temperature - Surface Roughness	[8]
Coconut Oil	M_0S_2	0.5% vol	- Cutting Zone Temperature - Surface Roughness	[9]
Soybean Oil	Boric Acid	3% wt	- Cutting Zone Temperature - Surface Roughness	[10]
Canola Oil	M_0S_2	0.5% vol	- Cutting Zone Temperature - Surface Roughness	[11]
Olive Oil	Al_2O_3	0.5% vol	- Metal chip morphology - Surface roughness	[12]

The lubricating function of nanoparticles is also enhanced by their ability to interact with metal surfaces via mild chemical reactions, forming an anti-wear layer [35]. In the machining process, extreme conditions such as high pressure and intense friction trigger the formation of a protective layer of nanoparticles, which is adaptive and extends the tool's service life while maintaining the workpiece's surface quality [45]. Experimental studies have shown that Al_2O_3-based nanofluids and coconut oil can reduce surface roughness (Ra) by more than 40%, while significantly reducing tool wear rates [27], [35], [41].

In industrial applications, vegetable nanofluids have been shown to deliver better performance. In processes such as turning, drilling, and milling of hard materials, such as stainless steel and titanium alloys, the use of palm or coconut oil enriched with nanoparticles reduces cutting temperature, friction, and tool wear [46], [20], [22]. Minimum Quantity Lubrication (MQL) technology enables the use of nanofluids in tiny yet efficient volumes, with low spray pressure directly reaching the cutting zone [47], [48], [49], [22].

Furthermore, the use of metal oxide-based nanoparticles in lubrication systems is also relatively safe for operators. Toxicology studies show that nanoparticles such as Al_2O_3 and SiO_2 do not cause irritation or toxicity in low doses, mainly when used in closed systems [50], [51]. This makes vegetable nanofluids a lubricant solution that is not only technologically superior, but also environmentally friendly and safe for occupational health [34], [52], [2].

Although the results are promising, developing nanofluid formulations still requires a multidisciplinary approach. Factors such as particle size, concentration, chemical stability, and compatibility with certain types of vegetable oils must be thoroughly considered [41].

5. RESULT AND DISCUSSION

Vegetable oils have gained significant attention as sustainable alternatives to mineral-based and synthetic coolants due to their high biodegradability, renewability, and low toxicity. However, their application in machining is often constrained by thermal degradation and insufficient lubrication under high cutting temperatures and loads. To address these limitations, many studies have been conducted to enhance vegetable oils by incorporating nanoparticles, thereby forming vegetable oil-based nanofluids. Various metal oxides (e.g., Al_2O_3, CuO), metal (Ag), and non-metallic nanoparticles (graphene, MoS_2, hBN) from the Research results can improve thermal conductivity, enhance heat dissipation, and reduce friction by forming protective tribological layers that fill surface microgaps. Therefore, these nanofluids contribute to reduced surface roughness (Ra), lower cutting zone temperatures, and extended tool life. The effectiveness of nanofluids is strongly influenced by nanoparticle concentration, with an optimal value of around 2.5% for Al_2O_3 maximizing performance. In contrast, excessive concentrations can cause aggregation and decreased stability. Furthermore, the Minimum Quantity Lubrication (MQL) system has been identified as an efficient and environmentally friendly approach for delivering vegetable oil-based nanofluids during machining.

5.1 Effect of Nanoparticle Type

The type of nanoparticle plays a critical role in determining the effectiveness of vegetable oil-based nanofluids. Metal oxide nanoparticles, such as Al_2O_3 and CuO, are widely reported to enhance thermal conductivity, resulting in lower cutting-zone temperatures and improved surface finish. Among these, Al_2O_3-based nanofluids are often considered more effective due to their good thermal stability, spherical morphology, and relatively high compatibility with vegetable oils. Several studies report significant reductions in surface roughness (Ra) when Al_2O_3 nanofluids are used in turning and milling processes, particularly compared with pure vegetable oils and conventional coolants.

Solid lubricant nanoparticles, such as MoS_2, graphene, and hexagonal boron nitride (hBN), exhibit superior tribological performance due to their layered crystal structures. These materials facilitate easy shear between sliding surfaces, resulting in lower friction coefficients and improved surface quality. Studies employing graphene and MoS_2 nanoparticles generally report greater reductions in surface roughness than those with metal oxide nanoparticles, especially under high-speed, high-load machining conditions. However, their effectiveness is strongly influenced by dispersion stability and particle size.

5.2 Effect of Nanoparticle Concentration

Nanoparticle concentration is one of the most influential parameters affecting nanofluid performance. Most studies indicate that surface roughness reduction improves with increasing nanoparticle concentration up to an optimal level. For example, Al_2O_3 nanofluids commonly exhibit optimal performance at concentrations around 2–3 wt%, where enhanced heat transfer and lubrication effects are maximized. Beyond this range, excessive nanoparticle content often leads to agglomeration, flocculation, and sedimentation, which deteriorate lubricant stability and reduce machining performance.

Differences in reported optimal concentrations across studies can be attributed to variations in base oil type, nanoparticle size, dispersion method, and machining parameters. Smaller nanoparticles tend to remain more stable at lower concentrations, while larger particles require careful dispersion techniques to prevent sedimentation. As a result, studies using ultrasonic homogenization and surfactants generally report better performance and higher stability at comparable concentrations.

5.3 Tribological Mechanism

The improvement in surface roughness achieved by vegetable oil-based nanofluids can be attributed to several synergistic tribological mechanisms. Nanoparticles can form a protective tribofilm at the tool-workpiece interface, reducing direct metal-to-metal contact. Additionally, the rolling and polishing effects of spherical nanoparticles help fill surface asperities and microgaps, resulting in smoother machined surfaces.

Layered nanoparticles, such as MoS_2 and graphene, further enhance lubrication by forming low-shear-strength films that reduce friction and wear. The combined cooling and lubrication effects lead to lower tool wear rates, improved tool life, and more stable machining processes. Variations in reported results across studies are mainly due to differences in nanoparticle characteristics, dispersion stability, machining conditions, and surface roughness evaluation methods.

6. CONCLUSION

Vegetable oil-based nanofluids demonstrate a clear trend toward improved machining performance while supporting environmentally friendly manufacturing practices. Most studies consistently report reductions in surface roughness, cutting temperature, and tool wear compared with conventional coolants, particularly when nanofluids are used in Minimum Quantity Lubrication (MQL) systems. These performance improvements are primarily due to enhanced thermal conductivity and the formation of protective tribological layers at the tool-workpiece interface.

Among the various nanoparticle types, solid lubricant nanoparticles such as MoS_2 and graphene generally exhibit superior friction reduction and surface finish improvement, especially under high cutting loads. In contrast, metal oxide nanoparticles such as Al_2O_3 provide more stable, reproducible performance due to their good dispersion and thermal stability. Most studies indicate that optimal nanoparticle concentrations lie within a limited range, typically 2–3 wt% for Al_2O_3-based nanofluids, beyond which agglomeration and sedimentation reduce stability and machining performance.

Despite these promising results, several Research gaps remain. The Influence of nanoparticle size distribution on dispersion stability and tribological behavior is not yet fully understood, and concentration thresholds that trigger agglomeration under different machining conditions are still inconsistently reported. In addition, long-term stability, potential health and safety impacts, and the scalability of vegetable oil-based nanofluids require further investigation. Future Research should therefore focus on optimizing nanoparticle size ranges, identifying critical concentration limits before agglomeration occurs, and exploring bioderived or naturally sourced nanoparticles to further enhance sustainability without compromising machining performance.

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