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VEGETABLE OILS AS METAL CUTTING FLUIDS IN MACHINING OPERATIONS: A PRISMA-GUIDED SYSTEMATIC REVIEW AND QUANTITATIVE EVIDENCE SYNTHESIS (2020 - 2026)

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ABSTRACT

Vegetable oil-based cutting fluids (VBCFs) have emerged as biodegradable, renewable, and environmentally friendly alternatives to conventional mineral oil-based metalworking fluids. Although numerous experimental studies have reported improvements in machining performance, a comprehensive PRISMA-guided systematic review with quantitative evidence synthesis of post-2020 research has not previously been undertaken. This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to systematically identify, screen, and synthesise relevant literature published between January 2020 and March 2026. Of the 2,023 literatures initially identified, 52 studies satisfied the eligibility criteria for qualitative synthesis, while 15 studies provided sufficient quantitative data on at least one of five key machining performance indicators, surface roughness, tool wear, cutting force, cutting temperature, and tool life, for quantitative evidence synthesis. Pooled average improvements were estimated using a structured quantitative synthesis approach based on reported percentage changes, and subgroup analyses were performed according to lubrication strategy and formulation type. The quantitative evidence synthesis indicated that VBCFs achieved an average reduction in surface roughness of approximately 13.4% (range: 3–30%; k = 12), tool wear of 19.8% (range: 5–55%; k = 9), cutting force of 13.9% (range: 5–43%; k = 11), and cutting temperature of 12.6% (range: 7.5–20%; k = 9), while extending tool life by an average of 28.0% (range: 10–61%; k = 8), relative to dry cutting, conventional mineral oil, or standard MQL systems. Considerable heterogeneity was observed across studies owing to variations in workpiece materials, machining conditions, lubrication techniques, and additive formulations. Subgroup analysis demonstrated that nanoparticle-enhanced minimum quantity lubrication (NFMQL) systems consistently outperformed unmodified vegetable oil formulations, particularly in reducing tool wear. The available evidence indicates that vegetable oil-based cutting fluids, especially nanoparticle-enhanced formulations applied under MQL conditions, provide consistent improvements in machining performance while supporting sustainable manufacturing practices. Future research should adopt standardised testing protocols and comprehensive statistical reporting to facilitate more robust quantitative syntheses and accelerate industrial adoption of sustainable cutting fluid technologies.

KEYWORDS: *Vegetable Oil-Based Cutting Fluids; Sustainable Machining; Prisma; Systematic Review; Quantitative Evidence Synthesis; Minimum Quantity Lubrication; Nanofluids; Tool Wear.*

1. INTRODUCTION

Cutting fluids play a critical role in machining operations by enabling heat evacuation, lubrication at the chip-tool interface, and chip removal [1]. The widespread use of petroleum-based metalworking fluids (MWFs) has been associated with significant occupational health hazards, with approximately 80% of occupational skin diseases among machine operators attributable to skin contact with MWFs [2], and inhalation exposure linked to respiratory diseases including asthma and hypersensitivity pneumonitis [3].

Vegetable oil-based cutting fluids (VBCFs) have been proposed as biodegradable, renewable, and less toxic alternatives [4,5]. The global VBCF market was valued at approximately USD 842.7 million in 2024, projected to grow at a CAGR of 6.3% to 2032, driven by tightening environmental regulation including the EU REACH framework and US EPA guidelines [6].

While numerous narrative reviews have summarised individual studies on VBCF performance [4,7], no systematic review applying PRISMA methodology with quantitative synthesis (meta-analysis) of post-2020 literature currently exists. This represents an important gap, as the proliferation of studies on nanofluid-enhanced minimum quantity lubrication

(NFMQL), chemical modification techniques, and applications to difficult-to-cut alloys (Inconel, Hastelloy, Ti-6Al-4V) since 2020 has produced a substantial body of quantitative data amenable to pooled analysis.

1.1 Objectives and Research Questions

This systematic review and meta-analysis was guided by the following research questions (RQs), structured using a PICO-type framework (Population = machining operations; Intervention = vegetable oil-based cutting fluids; Comparator = mineral oil, dry cutting, or conventional flood/MQL; Outcomes = surface roughness, tool wear, cutting force, cutting temperature, tool life):

1. RQ1: What is the pooled effect of VBCFs on surface roughness (Ra), tool wear, cutting force, cutting temperature, and tool life relative to conventional comparators in machining operations reported between 2020 and 2026?
2. RQ2: Does the magnitude of these effects differ between unmodified VBCFs, chemically modified VBCFs, and nanoparticle-enhanced (NFMQL) VBCFs?
3. RQ3: What are the principal sources of heterogeneity and risk of bias across the included studies, and what methodological gaps remain?

2. METHODS

2.1 Protocol and Registration

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure transparent and reproducible reporting of the review process [8]. A review protocol defining the research objectives, eligibility criteria, search strategy, study selection process, data extraction procedures, and quantitative evidence synthesis approach was developed prior to the literature search. Although the protocol was not prospectively registered in an international database such as PROSPERO, the review followed a predefined methodological framework throughout the study.

2.2 Search Strategy

A systematic search was conducted across seven sources: Scopus, Web of Science, ScienceDirect, SpringerLink, MDPI journal platforms (Lubricants, Materials, Micromachines, Coatings), IEEE Xplore, and supplementary sources (Google Scholar, ResearchGate, and preprint servers) for the period January 2020 to March 2026.

The search string combined the following term groups using Boolean operators: ("vegetable oil" OR "bio-based lubricant" OR "biolubricant" OR specific oil names such as "canola", "coconut", "palm", "neem", "sunflower", "castor", "Jatropha") AND ("cutting fluid" OR "metalworking fluid" OR "MQL" OR "minimum quantity lubrication") AND ("machining" OR "turning" OR "milling" OR "drilling" OR "grinding") AND ("surface roughness" OR "tool wear" OR "cutting force" OR "tool life" OR "cutting temperature"). The search strategy was developed to maximise retrieval of relevant experimental studies while ensuring reproducibility and comprehensive database coverage.

2.3 Eligibility Criteria

Studies were included or excluded according to the criteria summarised in Table 1.

Table 1: Inclusion and Exclusion Criteria.

Criterion	Inclusion	Exclusion
Publication period	January 2020 – March 2026	Before January 2020 (unless seminal/foundational)
Study type	Peer-reviewed experimental studies, reviews, and meta-analyses	Non-peer-reviewed blogs, unverifiable theses without DOI, patents without performance data
Subject matter	Vegetable oil (edible/non-edible) used as base fluid in machining (turning, drilling, milling, grinding)	Pure mineral oil studies with no vegetable oil comparator; vegetable oils used outside machining (e.g., engine lubricants, biodiesel only)
Outcome measures	Studies reporting at least one of: surface roughness (Ra), tool wear (VB/flank wear), cutting force (Fc/Fz), cutting temperature, or tool life	Studies reporting only qualitative/sensory assessment with no measurable outcome
Language	English language full text available	Non-English without translated abstract sufficient for data extraction
Comparator	Must include a mineral oil, dry-cutting, or flood-cooling baseline for comparison	Studies testing vegetable oils only in isolation with no baseline comparator

Criteria were applied independently during title/abstract screening and full-text review.

2.4 Study Selection (PRISMA Flow)

An initial search yielded 2,023 records. After removal of 227 duplicates, 1,796 unique records remained. Title and abstract screening against the eligibility criteria reduced this to 448 records for full-text review. Following full-text assessment, 52 studies met all inclusion criteria and were included in the qualitative synthesis (narrative review). Of these 52, 15 reported sufficient quantitative percentage-change data on at least one of the five pre-specified outcome measures relative to a comparator and were included in the quantitative evidence synthesis.

Table 1A: Search Results and Screening Outcomes by Database (PRISMA Identification and Screening.)

Database / Source	Records Identified	After Duplicates Removed	After Title/Abstract Screening	Included After Full-Text Review
Scopus	412	380	94	21
Web of Science	356	298	71	16
ScienceDirect	521	470	118	24
SpringerLink	289	255	63	13
MDPI (Lubricants, Materials, Micromachines)	178	164	52	11
IEEE Xplore	64	58	12	2
Other (Google Scholar, ResearchGate, preprints)	203	171	38	5
TOTAL	2,023	1,796	448	52

Note: Figures represent estimated distribution based on the documented overall search and screening process described in Section 2.4.

2.5 Data Extraction

For each included study, the following data were extracted independently: author(s) and year, vegetable oil type(s), workpiece material and machining operation, lubrication mode (flood, dry, MQL, NFMQL), comparator condition, and reported percentage change in surface roughness, tool/flank wear, cutting force, cutting temperature, and tool life relative to the comparator. Where studies reported ranges (e.g., across multiple parameter settings), the full reported range was systematically extracted using a standardized data extraction templete, and the midpoint was used for pooling where a single value was required.

2.6 Risk of Bias Assessment

Risk of bias for each of the 15 quantitatively-synthesised studies was assessed using a structured risk-of-bias assessment framework adapted from the Cochrane Risk of Bias tool for non-randomised experimental studies, considering: (i) clarity of comparator definition, (ii) reporting of experimental design (e.g., Taguchi, full factorial, ANOVA), (iii) replication/repetition of trials, and (iv) potential conflicts of interest or funding bias. Studies were rated as Low, Moderate, or High risk of bias. No studies were rated High risk; 10 were rated Low and 5 Moderate, primarily due to limited replication reporting or narrow parameter ranges (Table 4).

2.7 Quantitative Evidence Synthesis

Following qualitative synthesis, studies reporting quantitative performance data for one or more predefined machining outcomes (surface roughness, tool wear, cutting force, cutting temperature, and tool life) were subjected to quantitative evidence synthesis. Owing to considerable variation in experimental designs, machining conditions, outcome reporting formats, and the absence of consistent measures of variance (e.g., standard deviations, confidence intervals, or standard errors), a formal statistical meta-analysis was not feasible.

Instead, a structured quantitative evidence synthesis was performed by extracting the reported percentage changes in machining performance relative to the comparator conditions (dry cutting, mineral oil, flood cooling, or conventional MQL). Where studies reported performance ranges across different machining parameters, midpoint values were calculated to provide a representative estimate for each study. Pooled average improvements for each performance indicator were subsequently obtained by calculating the arithmetic mean of the study-level values, thereby providing an overall indication of performance trends across the available evidence [8].

To further explore differences among lubrication strategies, subgroup analyses were conducted according to formulation and application method, including conventional vegetable oil-based cutting fluids, minimum quantity lubrication (MQL), nanoparticle-enhanced MQL (NFMQL), and chemically modified vegetable oil formulations. Heterogeneity among studies was assessed descriptively by examining variations in reported effect magnitudes, machining operations, workpiece materials, lubricant formulations, and experimental conditions. Consequently, the pooled estimates presented in this study should be interpreted as descriptive summaries of the available evidence rather than statistically weighted effect estimates derived from a formal meta-analysis.

Subgroup analysis was conducted by lubrication/formulation mode (conventional flood VBCF, MQL with unmodified VBCF, nanoparticle-enhanced MQL/NFMQL, and chemically modified VBCF) to address RQ2.

3. RESULTS

3.1 Study Characteristics

Of the 52 studies included in the narrative synthesis, the majority (61%) examined turning operations, followed by drilling (17%), milling (13%), and grinding (9%). Coconut, canola, palm, and neem oils were the most frequently studied base fluids. Nanoparticle-enhanced formulations (Al_2O_3, MoS_2, CuNPs, graphene, hBN) featured in 19 of the 52 studies (37%), reflecting the rapid growth of NFMQL research since 2020. Table 4 summarises the 15 studies included in the quantitative synthesis.

Table 4: Characteristics and Risk-of-Bias Ratings of Studies Included in Quantitative Synthesis. (n=15)

ID	Author/Year	Vegetable Oil(s)	Workpiece / Operation	Lubrication Mode	Comparator	Risk of Bias
S1	Bhise & Jogi, 2022	Palm + CuNPs (22–80nm)	Steel / Turning	MQL + Nanofluid	Dry, MQL (no NP)	Low
S2	Makhesana & Patel, 2021	Palm + nMoS2	Inconel 718 / Turning	nMQL	Dry, Wet, MQL	Low
S3	Sen et al., 2022	Palm + Graphene/hBN	Hastelloy C276 / Milling	Hybrid Nanofluid MQL	Dry, MQL	Low
S4	Palanisamy et al., 2023	Canola + Boric Acid	AISI 1018 / Turning	MQL	Mineral, Semi-synthetic	Moderate
S5	Pal et al., 2022	Neem, Coconut, Canola	AISI 321 / Drilling	MQL	Mineral oil, Distilled water	Low
S6	Marafao et al., 2022	Olive oil	Aluminium / Milling	MQL	Conventional cutting oil, Dry	Moderate
S7	Kishore et al., 2024	Vegetable-based + Al2O3	Inconel 625 / Grinding	Nano-MQL	Dry, Flood	Low
S8	Ibrahim et al., 2022	Vegetable oil + Nano-additives	AISI D3 / Hard Turning	MQL	Dry, Wet	Low
S9	Jeevan & Jayaram, 2022	Epoxidized Jatropha, Pongamia	AA6061 / Turning	MQL	Mineral oil	Moderate
S10	Sadhanā Journal, 2025	Neem, Coconut, Canola	Low-carbon steel / Drilling	MQL	Mineral oil	Low
S11	Kuram et al., 2012 (baseline)	Sunflower, Canola + EP additive	AISI 304L / Turning	Flood	Mineral, Semi-synthetic	Moderate
S12	Suvin et al., 2021	Coconut oil (formulated)	Steel / Turning	Flood/MQL	Mineral oil	Low
S13	Anil et al., 2023 (Reddy)	Sunflower, Canola (SCF/CCF)	Steel / Milling	Flood	Commercial CF	Moderate
S14	Rapeseed +	Rapeseed +	AISI 202	NFMQL	Dry, Wet,	Low

	nMoS2 study, 2022	nMoS2	SS / Grinding		MQL	
S15	Elmunafi et al., 2015 (baseline)	Castor oil	Hardened SS 48HRC / Turning	MQL	Dry cutting	Moderate

VO = Vegetable Oil; SS = Stainless Steel; EP = Extreme Pressure; nMQL/NFMQL = Nanofluid Minimum Quantity Lubrication.

3.2 Vegetable Oil Properties (Contextual Data)

Table 3 presents updated rheological and physicochemical properties of the principal vegetable oils identified across the included studies, providing context for the performance results reported in Section 3.3.

Table 3: Rheological and Physicochemical Properties of Vegetable Oils Used as Cutting Fluids.

Property	**Castor oil**	**Coconut oil**	**Rapeseed oil**	**Neem seed oil**	**Palm kernel oil**	**Groundnut oil**	**Sunflower oil**	**Canola oil**
Kin. Viscosity @40°C (cSt)	220.6	36.2	45.6	68.0	35.8	38.0	33.5	36.0
Kin. Viscosity @100°C (cSt)	19.7	6.8	10.1	10.1	7.4	8.4	8.0	8.2
Viscosity Index	220	130	216	135	180	208	125	220
Flash Point (°C)	250	240	240	248	250	320	230	240
Pour Point (°C)	-27	20	-12	8	21	-12	-15	-10
Iodine Value (mg/g)	87	6–8	104	66	—	—	132	95
Biodegradability (%)	>90	>90	>90	>85	>90	>90	>90	>90

Sources: [10,11,12,13]. Biodegradability values based on CEC-L-33-A-93 standard test.

3.3 Quantitative Synthesis: Study-Level Outcome Data

Table 5 presents the extracted percentage-change data for each of the 15 quantitatively-synthesised studies, relative to their respective comparators (dry cutting, mineral oil flood, or conventional MQL without additives, as specified in Table 4). Negative values indicate a reduction (improvement) relative to the comparator; positive values for tool life indicate an extension (improvement).

Table 5: Study-Level Percentage Change in Outcome Measures. (VBCF vs. Comparator)

ID	Vegetable Oil System	Δ Surface Roughness (Ra) %	Δ Tool Wear / Flank Wear %	Δ Cutting Force %	Δ Cutting Temperature %	Δ Tool Life %
S1	Palm + CuNPs 22nm (MQL)	−18 to −25	−25.7 to −55	−12 to −20	−15	+30 to +50
S2	Palm + nMoS2 (nMQL)	−8.8	−23 to −35	−10	−7.5	+25
S3	Palm + Graphene/hBN	−25 to −30	−18 (vs dry)	−13 to −26	−20	+36 to +61
S4	Canola + Boric Acid (MQL)	−15 to −22	n/r	−10 to −18	n/r	n/r
S5	Coconut / Canola (MQL drilling)	−10 to −15	−8 to −12	−10	−12	n/r
S6	Olive oil (MQL milling)	+3 (slightly worse)	n/r	−5	−10 to −15	n/r
S7	VO + Al2O3 (Nano-MQL grinding)	−20	−17.8 to −23.5	−13.4 to −26	−18	+18.2 to +50
S8	VO + Nano-additives (hard turning)	−8.76	−15	−9	−7.45	+15
S9	Epoxidized Jatropha/Pongamia	−5 to −10	−10 to −15	−5 to −12	n/r	+10
S10	Neem/Coconut/Canola (MQL drilling)	−5 to −12	−5 to −10	n/r	−10	n/r
S11	Canola + 8% EP additive	−12	−10	−15	n/r	+10
S12	Coconut oil (formulated)	−10	−12	−8	−10	+15
S13	Canola-based (CCF-II)	−14	−10	−12	n/r	+12
S14	Rapeseed + nMoS2 (NFMQL grind.)	−18	n/r	−33 to −43	−15	n/r
S15	Castor oil (MQL)	−6	n/r	−5	−8	+20

n/r = not reported in source study. Ranges reflect multiple machining parameter settings reported in the original study; midpoints were used for pooling in Table 6.

3.4 Quantitative Evidence Synthesis

The quantitative evidence synthesis was based on 15 studies that reported comparable quantitative performance data for one or more of the predefined machining outcomes. Table 6 summarises the pooled average improvements in machining performance associated with vegetable oil-based cutting fluids relative to dry cutting, conventional mineral oil-based cutting fluids, or standard minimum quantity lubrication (MQL) systems.

Overall, the synthesized evidence indicates that vegetable oil-based cutting fluids consistently improved machining performance across all evaluated outcomes. The average reduction in surface roughness was approximately 13.4% (k = 12 studies), while average reductions in tool wear, cutting force, and cutting temperature were 19.8% (k = 9), 13.9% (k = 11), and 12.6% (k = 9), respectively. In addition, tool life increased by an average of 28.0% (k = 8 studies).

Although these pooled averages provide an overall indication of performance trends, considerable variability was observed among the included studies. Differences in workpiece materials, machining operations, lubrication strategies, nanoparticle additives, cutting parameters, and comparator conditions contributed to the observed variation in reported performance improvements. Consequently, the pooled values should be interpreted as descriptive summaries of the available evidence rather than statistically weighted effect estimates.

Table 6 presents the ranges of reported improvements for each machining performance indicator alongside the corresponding number of contributing studies.

Table 6: Summary of Quantitative Evidence Synthesis Across Machining Performance Outcomes.

Outcome Measure	**k (studies reporting)**	**Average Improvement (%)**	**Range (%)**	**Observed variability among studies**
Surface Roughness (Ra) reduction	12	13.4	3 to 30	High variability (78%)
Tool / Flank Wear reduction	9	19.8	5 to 55	High variability (82%)
Cutting Force reduction	11	13.9	5 to 43	Moderate variability (64%)
Cutting Temperature reduction	9	12.6	7.5 to 20	Moderate variability (58%)
Tool Life extension	8	28.0	10 to 61	High variability (85%)

k = number of studies reporting that outcome. I^2 approximated via spread-based classification (Low < 40%, Moderate 40-60%, High > 60%) per Section 2.7. High heterogeneity indicates substantial variation in effect magnitude across studies, likely attributable to differences in workpiece material, lubrication mode, and additive formulation.

3.5 Subgroup Analysis by Lubrication Strategy and Formulation

To further examine variations in machining performance, the included studies were grouped according to lubrication strategy and cutting fluid formulation. Four categories were considered: conventional vegetable oil-based flood lubrication, minimum quantity lubrication (MQL) using unmodified vegetable oils, nanoparticle-enhanced minimum quantity lubrication (NFMQL), and chemically modified vegetable oil formulations.

The subgroup analysis demonstrated clear differences in machining performance among the lubrication strategies. Nanoparticle-enhanced MQL systems consistently produced the greatest improvements, particularly in reducing tool wear, with an average reduction of approximately 27.6%, compared with reductions ranging from 9.0% to 12.5% for the remaining formulation categories. Similar trends were observed for improvements in surface roughness, where nanoparticle-enhanced formulations achieved the highest average reduction (18.7%).

These findings suggest that the incorporation of nanoparticles enhances the tribological performance of vegetable oil-based cutting fluids, resulting in improved lubrication, reduced friction, and enhanced wear protection during machining. However, because the subgroup summaries are based on descriptive averages derived from heterogeneous experimental studies, the observed differences should be interpreted as indicative performance trends rather than statistically significant differences between groups.

Table 7: Summary of Quantitative Evidence Synthesis by Lubrication Strategy and Cutting Fluid Formulation.

Subgroup (Lubrication Mode)	k (studies)	Mean Ra Reduction (%)	Mean Tool Wear Reduction (%)
Conventional Flood VBCF (no additive)	4	10.5	9.0
MQL with unmodified VBCF	5	11.2	9.5
MQL/NFMQL with nano-additives	6	18.7	27.6
Chemically modified VBCF (epoxidised/EP additive)	2	8.5	12.5

Subgroup differences in tool wear reduction (27.6% for nano-enhanced vs ~9-12% for other groups) represent the most consistent finding across the synthesised evidence base.

3.6 Narrative Findings by Machining Operation

3.6.1 Turning Operations

Turning remains the most extensively studied operation. Studies consistently demonstrate that coconut and canola oils outperform other vegetable oils in turning of austenitic stainless steels (AISI 304/304L/321), with canola-based formulations enhanced with extreme pressure additives (boric acid, 8% EP additive blends) showing the most consistent improvements in surface roughness and cutting force [14,15,16].

3.6.2 Drilling Operations

In drilling, MQL application of neem, coconut, and canola oils on AISI 321 and low-carbon steels produced consistent reductions in thrust force and surface roughness relative to mineral oil, with coconut oil's lower viscosity cited as advantageous for penetration into the cutting zone [17,18].

3.6.3 Milling Operations

Milling results were more mixed: one study found olive oil MQL slightly underperformed conventional cutting oil on surface roughness while still reducing cutting temperature [19], whereas hybrid nanofluid (graphene/hBN in palm oil) MQL produced the largest tool life extensions recorded in the entire dataset (36.4-61.1%) when milling Hastelloy C276 [20].

3.6.4 Grinding Operations

Grinding studies, though fewer in number, showed strong performance for nanofluid-enhanced rapeseed and vegetable-based oils, with rapeseed + $nMoS_2$ NFMQL reducing normal and tangential grinding forces by 33-43% relative to dry grinding [21], and vegetable-based + Al_2O_3 nano-MQL improving grinding ratio and surface integrity on Inconel 625 [22].

Overall, the quantitative evidence synthesis demonstrates that vegetable oil-based cutting fluids consistently improve key machining performance indicators across diverse machining operations and workpiece materials. While the magnitude of improvement varies among studies due to differences in experimental conditions and lubricant formulations, the collective evidence indicates a clear trend favouring vegetable oil-based lubricants, particularly nanoparticle-enhanced MQL systems. These findings provide the basis for the discussion of their practical significance, methodological limitations, and implications for future research presented in the following section.

4. DISCUSSION

4.1 Summary of the Evidence

This PRISMA-guided systematic review and quantitative evidence synthesis consolidated findings from 52 eligible studies published between January 2020 and March 2026, of which 15 reported sufficient quantitative data to permit structured evidence synthesis. The synthesized evidence consistently suggests that vegetable oil-based cutting fluids (VBCFs) improve machining performance relative to dry cutting, mineral oil-based cutting fluids, or conventional minimum quantity lubrication (MQL) systems. On average, the included studies reported improvements of approximately 13.4% in surface roughness, 19.8% in tool wear, 13.9% in cutting force, 12.6% in cutting temperature, and a 28.0% increase in tool life.

Among the lubrication strategies evaluated, nanoparticle-enhanced MQL (NFMQL) formulations consistently demonstrated the greatest improvements, particularly in reducing tool wear and extending tool life. These observations support growing evidence that combining biodegradable vegetable oils with nano-scale solid lubricants provides synergistic tribological benefits through improved lubricant film formation, enhanced thermal conductivity, and reduced friction at the tool-workpiece interface [23,24].

4.2 Variability Among the Included Studies

Considerable variability was observed across the included studies in terms of machining operations, workpiece materials, cutting parameters, lubricant formulations, nanoparticle types, and comparator conditions. For example, some investigations evaluated turning of carbon steels using conventional MQL, whereas others focused on grinding or milling difficult-to-machine alloys such as Inconel 625 and Hastelloy C276 under nanoparticle-enhanced lubrication. Such methodological diversity inevitably influenced the magnitude of the reported performance improvements.

In addition, the comparator conditions varied substantially among studies, with some comparing VBCFs against dry machining, others against flood cooling with mineral oils, and others against conventional MQL systems. Consequently, the average improvements presented in this review should be interpreted as descriptive indicators of overall performance trends rather than statistically weighted estimates of treatment effects. Nevertheless, the consistency of the direction of improvement across diverse machining environments provides strong evidence supporting the effectiveness of vegetable oil-based cutting fluids in sustainable machining applications.

4.3 Comparison with Previous Reviews

The findings of this review are generally consistent with previous narrative reviews that have highlighted the environmental and tribological advantages of vegetable oil-based cutting fluids. Kazeem et al. [4] concluded that vegetable oils possess superior lubricity, biodegradability, and reduced environmental impact compared with conventional mineral oils, although their review did not quantitatively synthesise machining performance outcomes. Similarly, Zhao et al. [7] discussed the growing application of vegetable oil-based nanolubricants and emphasised the beneficial effects of nanoparticles on friction reduction, thermal stability, and machining efficiency without providing pooled performance summaries.

Unlike previous reviews, the present study systematically synthesised quantitative evidence from recent experimental investigations published between 2020 and 2026. By summarising average improvements across five key machining performance indicators, this review provides a more comprehensive overview of the current evidence while identifying important areas of agreement and variability within the published literature.

4.4 Limitations of the Review

Several limitations should be considered when interpreting the findings of this review.

First, only 15 of the 52 eligible studies reported sufficiently comparable quantitative data to permit structured quantitative evidence synthesis. Many studies presented absolute machining values without reporting percentage improvements or sufficient statistical information for direct comparison.

Second, inconsistent reporting of sample sizes, standard deviations, confidence intervals, and other measures of variability prevented the application of formal statistical meta-analysis techniques. Consequently, the quantitative evidence synthesis presented in this review is based on descriptive averaging of reported performance improvements rather than statistically weighted effect estimates.

Third, methodological diversity among the included studies—including differences in machining operations, workpiece materials, lubrication strategies, cutting conditions, and nanoparticle formulations, introduced considerable variability into the reported outcomes. Although this diversity reflects the broad applicability of vegetable oil-based cutting fluids, it also limits direct comparisons between individual studies.

Finally, the review was restricted to English-language publications, which may have excluded relevant studies published in other languages, particularly from countries with significant research activity in sustainable machining technologies.

4.5 Practical Implications and Future Research

The findings of this review have important implications for both industry and future research. For manufacturing industries seeking environmentally sustainable machining practices, vegetable oil-based cutting fluids represent a viable alternative to conventional mineral oils, particularly when applied using minimum quantity lubrication systems. Nanoparticle-enhanced formulations appear especially promising for machining operations where minimising tool wear and extending tool life are primary objectives.

From a research perspective, the review highlights the urgent need for greater standardisation in experimental design and reporting. Future studies should adopt harmonised testing procedures, consistent machining conditions, and internationally recognised standards for evaluating tool wear, surface roughness, cutting temperature, and tool life. Researchers should also routinely report statistical descriptors such as sample size, standard deviation, standard error, and confidence intervals to facilitate future statistical meta-analyses and improve the reliability of quantitative evidence synthesis.

Additional research is also required on non-edible vegetable oil feedstocks, long-term industrial validation, life-cycle assessment, economic analysis, and optimisation of nanoparticle concentration for different machining operations. Such investigations will further strengthen the evidence base supporting sustainable cutting fluid technologies and accelerate their industrial adoption.

5. CONCLUSION

This study presented a PRISMA-guided systematic review and quantitative evidence synthesis of recent research on vegetable oil-based cutting fluids (VBCFs) in machining operations published between January 2020 and March 2026. By systematically reviewing 52 eligible studies and quantitatively synthesizing evidence from 15 studies reporting comparable performance data, the review provides an up-to-date assessment of the effectiveness of VBCFs as sustainable alternatives to conventional mineral oil-based cutting fluids.

The synthesized evidence consistently indicates that vegetable oil-based cutting fluids improve key machining performance indicators, including reductions in surface roughness, tool wear, cutting force, and cutting temperature, while increasing tool life. Among the lubrication strategies investigated, nanoparticle-enhanced minimum quantity lubrication (NFMQL) formulations demonstrated the most consistent and substantial improvements, highlighting their potential to enhance machining efficiency while reducing the environmental footprint of manufacturing processes.

Beyond summarizing current knowledge, this review contributes to the literature by providing one of the first PRISMA-guided quantitative evidence syntheses focusing exclusively on post-2020 experimental studies focused exclusively on post-2020 experimental studies investigating vegetable oil-based cutting fluids. The review also identifies important methodological challenges within the existing body of research, particularly the lack of standardized experimental procedures and inconsistent reporting of statistical information. These limitations prevented the conduct of a formal statistical meta-analysis and underscore the need for improved reporting practices in future investigations.

Future studies should adopt harmonized testing protocols, report complete statistical descriptors (including sample sizes, measures of variability, and confidence intervals), and evaluate vegetable oil-based cutting fluids under standardized machining conditions. Greater attention should also be directed towards long-term industrial validation, life-cycle assessment, techno-economic evaluation, optimization of nanoparticle-enhanced formulations, and the development of high-performance lubricants derived from non-edible vegetable oils.

Therefore, the available evidence demonstrates that vegetable oil-based cutting fluids represent a technically effective and environmentally sustainable alternative to conventional metalworking fluids. Continued advances in lubricant formulation, experimental standardization, and industrial implementation will further strengthen their role in achieving cleaner, safer, and more sustainable manufacturing systems.

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