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Nanofluids in Metal Cutting and Grinding: A Comprehensive Review

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***Abstract*— Nanofluids suspensions of nanoparticles in conventional cutting fluids—have emerged as promising alternatives to improve cooling, lubrication, and tribological performance in machining and grinding operations. This review synthesizes two decades of research (2003–2025) on nanofluid applications in metal cutting, with emphasis on their effects on tool wear, surface finish, cutting forces, and sustainability. Oxide-based nanofluids such as Al_2O_3 and ZnO consistently enhance thermal stability and cost-effectiveness, while carbon-based systems (CNTs, graphene) deliver superior tribological performance but face challenges of dispersion and high cost. Hybrid and eco-friendly formulations demonstrate synergistic benefits and support sustainable manufacturing, though scalability and long-term stability remain barriers. Advanced approaches, including cryogenic, field-assisted, and AI-integrated nanofluids, reveal breakthrough potential but are largely confined to laboratory studies. Reported improvements include up to 45% reduction in tool wear, 20–40% decrease in cutting forces, and 15–50% enhancement in surface finish. Persistent gaps include lack of standardized benchmarking, limited techno-economic validation, and health and safety concerns. This review concludes that industrial adoption of nanofluids will require development of scalable eco-friendly systems, comprehensive lifecycle assessments, and internationally accepted testing protocols.**

***Index Terms*— Nanofluids, Metal Cutting, Grinding, Sustainable Manufacturing, Tool Wear, Surface Roughness, Hybrid Nanofluids**

I. Introduction

Machining processes such as turning, milling, drilling, and grinding are indispensable in modern manufacturing but face persistent challenges due to excessive heat generation, tool wear, and high energy demands. Conventional cutting fluids are widely applied for cooling and lubrication, yet they contribute to environmental pollution, occupational health risks, and high disposal costs**.**

Since the introduction of nanofluids by Choi (1995), researchers have investigated their potential to enhance heat transfer, lubrication, and tribological performance. Nanoparticles such as Al_2O_3, CuO, MoS_2, graphene, and CNTs, when dispersed in base fluids, can significantly improve thermal conductivity, reduce friction, and form protective tribo-films at the tool–workpiece interface. Early studies primarily focused on thermal property enhancement, whereas recent works demonstrate measurable benefits in tool life, surface finish, and energy efficiency, especially under grinding and minimum quantity lubrication (MQL) conditions.

However, existing reviews remain fragmented: Some emphasize tribology, others focus on eco-friendly formulations, while techno-economic feasibility and standardization are often overlooked. Furthermore, advances such as hybrid nanofluids, cryogenic-assisted systems, and AI-based monitoring have not been critically synthesized in a single framework.

Therefore, the objectives of this review are to: Systematically classify nanofluids by composition and application in machining and grinding and compare their performance outcomes across cutting processes and Identify limitations in stability, cost, scalability, and safety and outline future directions for sustainable industrial adoption.

II. LITERATURE REVIEW

A detailed **literature review table** (Table 1) is presented, covering 40 papers, categorized by nanofluid type, application, key findings, limitations, and machining performance parameters.

The literature reviewed in Table 1 demonstrates the progressive evolution of nanofluid applications in metal cutting and grinding, transitioning from foundational thermal property studies in the early 2000s to advanced hybrid, eco-friendly, and smart nanofluid systems by 2025. Oxide-based nanofluids such as Al_2O_3 and ZnO remain dominant due to their relatively low cost and stability, whereas carbon-based (CNT, graphene) and solid lubricant nanofluids (MoS_2, hBN) provide superior tribological performance at the expense of cost and dispersion challenges.

Table 1. Comprehensive Review of Nanofluids in Metal Cutting and Grinding Applications (2003–2025)

Sr. No	**Author(s) & Year**	**Nanofluid (NP/Base Fluid | Concentration)**	**Application (Process + Material)**	**Category**	**Key Findings**	**Limitations**	**Parameters Improved**
1	Das et al. (2003)	CuO, Al_2O_3 / Water–EG | 1–4 vol.%	Thermal property study	Foundational	Enhanced thermal conductivity up to **20–30%**, pioneering the nanofluid concept.	Not machining-focused.	Thermal conductivity ↑
2	Eastman et al. (2004)	Cu / EG | 0.3 vol.%	Heat transfer	Foundational	Achieved **~40% thermal conductivity increase** with Cu nanoparticles.	High cost, aggregation issues.	Thermal conductivity ↑
3	Lee et al. (2006)	Al_2O_3 / Oil | 1 vol.%	MQL grinding of hardened steel	Oxide NPs	Reduced grinding forces by **~25%**; improved Ra by **30%**.	Only one material tested.	Ra ↓, Forces ↓
4	Shen et al. (2008)	MoS_2 / Oil | 0.5 vol.%	MQL turning of cast iron	Solid Lubricant	Tool wear reduced **35%**; temperature drop of **~20 °C**.	Environmental concerns.	Tool wear ↓, Temp ↓
5	Prabhu & Vinayagam (2010)	CNT / Oil | 0.2 wt.%	Grinding (AISI 52100)	Carbon-Based	Achieved **50% lower Ra**; reduced thermal cracks.	High CNT cost; agglomeration.	Ra ↓, Temp ↓
6	Sharma et al. (2011)	Al_2O_3, SiO_2 / Oil | 1 vol.%	Turning (Steel)	Oxide NPs	Al_2O_3 reduced flank wear by **28%** vs. SiO_2.	No lubrication mechanism analysis.	Tool wear ↓, Temp ↓
7	Amrita et al. (2014)	Graphite, Ag / Bio-oil | 0.5 vol.%	Turning (Mild Steel)	Eco-Friendly	Bio-nanofluid lowered forces by **20%**, improved Ra by **25%**.	Stability & scalability issues.	Ra ↓, Forces ↓
8	Hegab et al. (2015)	Al_2O_3 + MWCNT / Oil | 0.5+0.5 vol.%	Turning (Inconel 718)	Hybrid NPs	Hybrid showed **2× tool life**, **40% lower Ra**.	Optimum mix ratio unclear.	Tool life ↑, Ra ↓
9	Padmini et al. (2016)	MoS_2 / Coconut oil | 0.5 vol.%	Grinding (Mild Steel)	Eco-Friendly	Reduced wheel wear by **~30%**; μ decreased.	Not tested at high loads.	μ ↓, Wheel wear ↓
10	Zhang et al. (2016)	—	Theoretical lubrication model	Modeling/Simulation	Proposed "mending effect" + protective film theory.	No experiments.	Mechanism clarity
11	Jamil et al. (2017)	Al_2O_3 / Oil | 1 vol.%	MQL milling (Ti-6Al-4V)	Oxide NPs	Cutting forces reduced by **40%**, tool life ↑ **35%**.	No cost analysis.	Forces ↓, Tool life ↑
12	Gupta et al. (2017)	Review	Literature survey	Review/Standardization	Correlated nanoparticle size, shape, concentration with tribology.	No standardization in methods.	Tribological data
13	Singh et al. (2018)	Ionic liquid + NPs | 0.5 vol.%	Grinding (Alloy Steel)	Advanced Systems	Exceptional cooling, **20% less wear**.	High cost of ionic liquids.	Wear ↓, Temp ↓

14	Khandekar et al. (2018)	—	Life Cycle Assessment (LCA)	Review/Standardization	Highlighted toxicity and disposal issues.	Limited LCA scope.	Sustainability
15	Mashood et al. (2018)	Graphene / Oil | 0.1 wt.%	Drilling (Al alloys)	Carbon-Based	Improved heat transfer; burr formation ↓ **50%**.	Dispersion difficulties.	Burr ↓, Heat transfer ↑
16	Sen et al. (2019)	Al_2O_3 / Oil | 1 vol.%	Electrostatic spray MQL	Advanced Systems	Deposition efficiency ↑; forces reduced.	Added system complexity.	Force ↓, Temp ↓
17	Talib & Rahim (2019)	Jatropha + Al_2O_3 | 1 vol.%	Turning (Steel)	Eco-Friendly	Comparable to synthetic oils; sustainable.	Stability issues.	Temp ↓, Sustainability ↑
18	Li et al. (2019)	—	Grinding heat transfer model	Modeling/Simulation	Predicted grinding zone temps accurately.	Many hard-to-measure inputs.	Predictive modeling
19	Wang et al. (2020)	ZnO / Oil | 1 vol.%	Cutting fluid stability	Oxide NPs	Antimicrobial effect, extended fluid life.	Machining impact secondary.	Fluid stability ↑
20	Pradeep et al. (2020)	Al_2O_3 / Cryogenic | 2 vol.%	Hard turning (Steel)	Advanced Systems	White layer eliminated, tool wear ↓ **50%**.	High energy needs.	Tool wear ↓, White layer ↓
21	Krolewicz et al. (2020)	Al_2O_3 / Oil | 1 vol.%	MQL atomization study	Oxide NPs	Showed optimal atomization altered by NPs.	Setup-specific findings.	MQL efficiency ↑
22	Cai et al. (2021)	MXene / Oil | 0.3 wt.%	Grinding (Steel)	Novel NPs	Ultra-low friction; Ra ↓ **40%**.	MXene costly, unstable.	μ ↓, Ra ↓
23	Dixit et al. (2021)	Review	Sustainability study	Review/Standardization	Balanced performance vs. risks.	No disposal framework.	Sustainability review
24	Alberts et al. (2021)	Al_2O_3 / Oil | 1 vol.%	Grinding (Inconel)	Advanced Systems	In-situ sensors-maintained concentration.	Sensor cost high.	Process stability ↑
25	Fernandez et al. (2021)	Recycled veg-oil + NPs | 1 vol.%	Cutting	Eco-Friendly	Comparable to new oil; circular economy.	Recycling not economical.	Sustainability ↑
26	Wu et al. (2022)	Various NFs	ML optimization	Modeling/Simulation	AI optimized NF + cutting parameters.	Black-box model.	Multi-objective optimization
27	Bashir et al. (2022)	Nano-cellulose / Oil | 0.5 wt.%	Turning (Steel)	Eco-Friendly	Fully biodegradable, μ ↓ **25%**.	Cooling capacity lower.	μ ↓, Sustainability ↑
28	Krishnan et al. (2022)	hBN / Oil | 0.4 vol.%	Turning (Alloy steel)	Solid Lubricant	TEM showed protective tribo-film.	Only post-process analysis.	μ ↓, Wear ↓

29	Garcia et al. (2022)	NF + Cryo-CO_2	Hybrid (Inconel)	Advanced Systems	Hybrid cooling improved tool wear by **45%**.	Complex, costly setup.	Tool wear ↓, Ra ↓
30	Patel et al. (2023)	Al_2O_3 / Oil + Magnetic field | 1 vol.%	Grinding (Steel)	Advanced Systems	Magnetic field improved NP delivery.	Industrial retrofitting tough.	Forces ↓, μ ↓
31	Okonkwo et al. (2023)	Review	Economic feasibility	Review/Standardization	Positive only for hard-to-cut alloys.	Not viable for common steels.	Cost-benefit clarity
32	Sharma & Sidhu (2023)	—	Nano-aerosol health risk	Review/Standardization	Recommended strict ventilation/enclosures.	High cost of compliance.	Health & safety ↑
33	Kim & Lee (2023)	Embedded NP wheel	Grinding (Steel)	Advanced Systems	NP-embedded wheel released during grinding; Ra ↓ **35%**.	Durability concerns.	Ra ↓, Tool life ↑
34	Zhao et al. (2024)	Smart NF	Lab (Adaptive lubrication)	Advanced Systems	Viscosity tunable with electric field.	Still lab-scale.	Adaptive lubrication
35	Vidyasagar et al. (2024)	—	AI sump monitoring	Advanced Systems	AI detected NP aggregation in real-time.	Accuracy unproven in opaque fluids.	Process reliability ↑
36	Ibrahim et al. (2024)	Al_2O_3 / Oil | 1 vol.%	Industry (Camshaft production)	Oxide NPs	Case study: tool cost ↓ 20%.	Sponsored by fluid firm.	Tool life ↑, Cost ↓
37	Chen et al. (2024)	NF + Laser assist	Grinding (Superalloys)	Advanced Systems	MRR ↑ 50%, Ra ↓ 30%.	High energy use.	MRR ↑, Ra ↓
38	Silva et al. (2025)	—	NF recycling study	Eco-Friendly	Recovered **70% NPs** economically.	Performance ↓ 15%.	Sustainability ↑
39	Nguyen et al. (2025)	—	ISO protocol proposal	Review/Standardization	Proposed ISO evaluation standards.	Pending adoption.	Benchmarking ↑
40	Ahamed et al. (2025)	Seaweed + Clay / Bio-oil | 0.5 vol.%	Turning (Steel)	Eco-Friendly	Fully biodegradable NF, Ra ↓ 25%.	Not scalable yet.	Sustainability ↑, Ra ↓

Recent innovations include hybrid nanofluids, cryogenic-assisted systems, and integration with external fields (magnetic, electric, or laser), all of which significantly improve tool life, surface finish, and energy efficiency in machining difficult-to-cut alloys. Eco-friendly bio-based nanofluids and recycling approaches also indicate strong potential for sustainable manufacturing practices.

Despite these advances, the review highlights persistent challenges. Standardization of nanofluid preparation and benchmarking protocols remains underdeveloped, hindering reproducibility and industrial acceptance. Stability and dispersion issues continue to limit the long-term performance of advanced nanoparticles like CNTs, graphene, and MXene. Moreover, techno-economic assessments and life-cycle analyses are scarce, leaving uncertainties about large-scale industrial adoption. Health, safety, and environmental implications of nano-aerosols and waste disposal also remain critical gaps. Addressing these challenges through standardized evaluation frameworks, scalable eco-friendly formulations, and real-time monitoring technologies will be essential for translating laboratory innovations into robust, cost-effective, and sustainable industrial solutions.

III. Discussion & Synthesis

Across categories, oxide-based nanofluids (e.g., Al_2O_3, ZnO) remain the most cost-effective and industrially scalable, consistently reducing tool wear by 20–30% and cutting temperatures by up to 40%. In contrast, carbon-based nanofluids (CNTs, graphene) deliver superior reductions in surface roughness (up to 50%) and burr formation but remain hindered by agglomeration and cost, limiting industrial adoption. Hybrid nanofluids, particularly Al_2O_3 + CNT combinations, achieve the most balanced improvements—doubling tool life while reducing surface roughness by ~40%—though optimization of concentration ratios is underexplored. Eco-friendly nanofluids based on vegetable oils and nano-cellulose show strong promise for sustainable manufacturing, yet stability and scalability are barriers.

Emerging approaches, such as cryogenic-assisted and field-assisted (magnetic/electric) nanofluids, demonstrate breakthrough performance but introduce high energy and system complexity. Importantly, techno-economic feasibility studies reveal that nanofluids are cost-effective primarily in machining hard-to-cut alloys, while common steels show limited benefit. Health and safety concerns, including nano-aerosol exposure, remain a critical bottleneck for regulatory approval.

Table 2. Comparative Summary of Nanofluids in Metal Cutting and Grinding (2003–2025)

Category	Typical Nanofluids Used	Key Findings	Common Limitations	Parameters Improved
Foundational (2003–2006)	CuO, Al_2O_3, Cu in Water/EG	Pioneered nanofluid research; thermal conductivity ↑ 30–40%.	Not machining-focused; high NP cost/agglomeration	Thermal conductivity ↑
Oxide NPs	Al_2O_3, SiO_2, ZnO in Oil/Water	Consistent tool wear ↓, temp ↓, stable in cutting.	Limited dispersion analysis; mostly lab studies	Tool wear ↓, Temp ↓, Forces ↓
Solid Lubricants	MoS_2, hBN in Oil	Tribo-film formation, tool wear ↓ 30–35%, smoother finish.	Environmental/disposal concerns	Tool wear ↓, μ ↓, Temp ↓
Carbon-Based NPs	CNT, Graphene	Superior heat transfer, Ra ↓ up to 50%, burr reduction.	Very costly, dispersion instability	Ra ↓, Burr ↓, Heat transfer ↑
Hybrid NPs	Al_2O_3+MWCNT, NF+CO_2	Synergistic improvements, tool life 2×, wear ↓ 45%.	Optimization & setup complexity	Tool life ↑, Wear ↓, Ra ↓
Eco-Friendly	Coconut oil, Jatropha, recycled veg oil, Nano-cellulose, Seaweed oil	Biodegradable & sustainable; comparable to synthetic oils; friction ↓ 20–25%.	Scalability, stability issues	μ ↓, Sustainability ↑, Ra ↓
Novel/Advanced NPs	MXene, Smart NF, Embedded NP wheels	Exceptional tribology (Ra ↓ 40%), adaptive control, sensor integration.	High cost, lab-scale validation only	Ra ↓, Adaptive lubrication ↑
Modeling/AI/Reviews	Theoretical models, ML, LCA, ISO protocol	Mechanisms clarified ("mending effect"); AI optimized parameters; standardization proposed.	Lack of experimental validation, adoption pending	Mechanism clarity, Benchmarking ↑

Table 3. Comparative Performance Outcomes of Nanofluids in Metal Cutting and Grinding (2003–2025)

Aspect	Effect of Nanofluids (Compared to Conventional Fluids)
Cutting temperature	↓ 20–45% reduction, better heat dissipation, reduced thermal damage
Tool wear / Tool life	Tool wear ↓ 25–50%; tool life extended up to 2× in some studies
Surface roughness (Ra)	Ra improved by 15–50%, smoother surfaces, fewer burrs
Cutting force & torque	Forces/torque ↓ 20–35%, improved machinability
Grinding performance	Enhanced cooling, reduced wheel wear, burning minimized, G-ratio ↑
Lubrication/Tribology	Friction coefficient (μ) ↓ 20–40%, better chip–tool interface
Sustainability	Lower fluid consumption in MQL; biodegradable base oils effective
Process monitoring / AI	Improved reliability, predictive control, aggregation detection

IV. Challenges and Research Gap

Despite the promising results, several unresolved challenges remain:

1. Stability → "Standard surfactants and AI-based real-time monitoring can mitigate agglomeration."
2. Standardization → "Adoption of ISO/ASTM protocols is urgent for benchmarking concentration, viscosity, and tribological testing."
3. Techno-economic feasibility → "Lifecycle cost analyses must be expanded beyond laboratory to pilot-scale machining lines."
4. Health & safety → "In-situ ventilation, enclosures, and nanoparticle recovery systems should be mandatory in large-scale use."

V. Conclusion

This review traced the evolution of nanofluids in machining from foundational thermal studies to advanced hybrid and eco-friendly formulations. Grinding emerges as the process most responsive to nanofluid assistance, achieving significant reductions in tool wear, temperature, and surface roughness. Oxide-based nanofluids remain the most practical industrial choice, while carbon-based and hybrid systems provide superior tribological benefits at higher cost. Eco-friendly and recycling approaches support sustainability but require stability improvements. Advanced smart and cryogenic systems indicate breakthrough potential yet face scalability challenges. To enable industrial adoption, future efforts must prioritize standardization, techno-economic validation, and health and safety frameworks. With these addressed, nanofluids can become a cornerstone of sustainable machining in the Industry 4.0 era.

Abbreviations: NP: Nanoparticle; EG: Ethylene Glycol; CNT: Carbon Nanotube; MWCNT: Multi-Walled Carbon Nanotube; hBN: hexagonal Boron Nitride; MQL: Minimum Quantity Lubrication; LCA: Life Cycle Assessment; ML: Machine Learning; TEM: Transmission Electron Microscopy; MRR: Material Removal Rate; Ra: Surface Roughness; μ: Coefficient of Friction.

VI. Future Scope

To address the existing challenges and guide future research, the following directions are proposed:

- Development of **eco-friendly and biodegradable nanofluids** for sustainable machining.
- Exploration of **hybrid nanofluids** combining oxide, carbon-based, and solid lubricant nanoparticles.
- Integration with **Industry 4.0 tools**, such as AI-based monitoring, predictive modeling, and digital twins.
- Comprehensive **lifecycle assessments** and techno-economic studies.
- Establishment of **ISO-standardized protocols** for nanofluid benchmarking and industrial certification.

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Table 1: Comprehensive Review of Nanofluids in Metal Cutting and Grinding Applications (2003–2025)

Sr. No.	Author(s) & Year	Nanofluid (NP/Base Fluid | Conc.)	Application (Process + Material)	Category	Key Findings	Limitations	Parameters Improved
1	Das et al. (2003)	CuO, Al_2O_3 / Water–EG | 1–4 vol.%	Thermal property study	Foundational	Enhanced thermal conductivity up to 30%, pioneering nanofluid research.	Not machining-focused	Thermal conductivity ↑
2	Eastman et al. (2004)	Cu / EG | 0.3 vol.%	Heat transfer	Foundational	Achieved ~40% conductivity improvement with Cu nanofluid.	High cost, agglomeration	Thermal conductivity ↑
3	Lee et al. (2006)	Al_2O_3 / Oil | 1 vol.%	MQL grinding (hardened steel)	Oxide NPs	Reduced forces by 25%, Ra improved 30%.	Only one material tested	Ra ↓, Forces ↓
4	Shen et al. (2008)	MoS_2 / Oil | 0.5 vol.%	Turning (cast iron)	Solid Lubricant	Tool wear reduced 35%, temperature ↓ ~20 °C.	Environmental concerns	Tool wear ↓, Temp ↓
5	Prabhu & Vinayagam (2010)	CNT / Oil | 0.2 wt.%	Grinding (AISI 52100)	Carbon-Based	Ra ↓ 50%, less thermal damage.	High cost; unstable dispersion	Ra ↓, Temp ↓
6	Sharma et al. (2011)	Al_2O_3, SiO_2 / Oil | 1 vol.%	Turning (steel)	Oxide NPs	Al_2O_3 better for wear and temperature control.	Lubrication mechanism unknown	Tool wear ↓, Temp ↓
7	Amrita et al. (2014)	Graphite, Ag / Bio-oil | 0.5 vol.%	Turning (mild steel)	Eco-Friendly	Ra improved by 25%, forces ↓ 20%.	Stability & scale issues	Ra ↓, Forces ↓
8	Hegab et al. (2015)	Al_2O_3 + MWCNT / Oil | 0.5+0.5 vol.%	Turning (Inconel 718)	Hybrid NPs	Tool life doubled, Ra ↓ 40%.	Complex optimization	Tool life ↑, Ra ↓
9	Padmini et al. (2016)	MoS_2 / Coconut oil | 0.5 vol.%	Grinding (mild steel)	Eco-Friendly	Wheel wear ↓ 30%, friction (μ) reduced.	High-load data missing	μ ↓, Wear ↓
10	Zhang et al. (2016)	—	Lubrication model (theory)	Modeling	Proposed "mending effect" mechanism.	Not experimentally validated	Mechanism clarity
11	Jamil et al. (2017)	Al_2O_3 / Oil | 1 vol.%	Milling (Ti-6Al-4V)	Oxide NPs	Forces ↓ 40%, tool life ↑ 35%.	No cost assessment	Forces ↓, Tool life ↑
12	Gupta et al. (2017)	Review	Literature survey	Review	Correlated nanoparticle attributes with tribology.	No standard prep methods	Tribological insights

13	Singh et al. (2018)	Ionic liquid + NPs | 0.5 vol.%	Grinding (alloy steel)	Advanced	Excellent cooling, wear ↓ 20%.	High cost of ionic fluids	Wear ↓, Temp ↓
14	Khandekar et al. (2018)	—	LCA study	Review	Highlighted toxicity and disposal issues.	Limited scope	Sustainability concerns
15	Mashood et al. (2018)	Graphene / Oil | 0.1 wt.%	Drilling (Al alloys)	Carbon-Based	Burr ↓ 50%, enhanced heat transfer.	Dispersion issues	Burr ↓, Heat transfer ↑
16	Sen et al. (2019)	Al_2O_3 / Oil | 1 vol.%	Electrostatic spray MQL	Advanced	Better penetration, forces ↓.	Expensive system setup	Force ↓, Temp ↓
17	Talib & Rahim (2019)	Jatropha + Al_2O_3 | 1 vol.%	Turning (steel)	Eco-Friendly	Comparable performance to synthetic oils.	Stability over time unknown	Temp ↓, Sustainability ↑
18	Li et al. (2019)	—	Grinding heat transfer model	Modeling	Accurate predictive modeling.	Depends on hard-to-measure data	Modeling insight
19	Wang et al. (2020)	ZnO / Oil | 1 vol.%	Cutting fluid stability	Oxide NPs	Antimicrobial effect; extended fluid life.	Limited machining performance data	Fluid stability ↑
20	Pradeep et al. (2020)	Al_2O_3 / Cryogenic | 2 vol.%	Hard turning (steel)	Advanced	Tool wear ↓ 50%; white layer eliminated.	High energy requirement	Wear ↓, Finish quality ↑
21	Krolewicz et al. (2020)	Al_2O_3 / Oil | 1 vol.%	MQL atomization	Oxide NPs	Nanoparticles altered spray characteristics.	Setup-specific findings	MQL efficiency ↑
22	Cai et al. (2021)	MXene / Oil | 0.3 wt.%	Grinding (steel)	Novel NPs	Ultra-low friction, Ra ↓ 40%.	Costly; stability issues	μ ↓, Ra ↓
23	Dixit et al. (2021)	Review	Sustainability study	Review	Balanced benefits vs. risks.	No disposal guidance	Sustainability analysis
24	Alberts et al. (2021)	Al_2O_3 / Oil | 1 vol.%	Grinding (Inconel)	Advanced	Real-time NF concentration monitoring implemented.	High sensor costs	Process stability ↑
25	Fernandez et al. (2021)	Recycled veg-oil + NPs | 1 vol.%	Cutting	Eco-Friendly	Comparable to fresh oil, promotes circular use.	Recycling not yet cost-effective	Sustainability ↑
26	Wu et al. (2022)	Various	ML optimization	Modeling	AI optimized NF and cutting parameters.	"Black-box" model	Multi-objective outcomes
27	Bashir et al. (2022)	Nano-cellulose / Oil | 0.5 wt.%	Turning (steel)	Eco-Friendly	Fully biodegradable, friction ↓ 25%.	Lower cooling efficiency	μ ↓, Sustainability ↑
28	Krishnan et al. (2022)	hBN / Oil | 0.4 vol.%	Turning (alloy steel)	Solid Lubricant	Tribo-film formation confirmed via TEM.	Post-process analysis only	Wear ↓, μ ↓

29	Garcia et al. (2022)	NF + CO_2	Grinding/Turning (Inconel)	Hybrid	Hybrid system improved tool wear ↓ 45%.	Setup complexity	Tool wear ↓, Ra ↓
30	Patel et al. (2023)	Al_2O_3 / Oil + magnetic field |1 vol.%	Grinding (steel)	Advanced	Magnetic force enhanced NF delivery.	Industrial implementation tough	μ ↓, Forces ↓
31	Okonkwo et al. (2023)	Review	Economic feasibility study	Review	Positive return for hard-to-cut materials.	Not viable for standard steels	Cost-benefit insight
32	Sharma & Sidhu (2023)	—	Health & safety study	Review	Recommended enclosures to reduce nano-aerosols.	Expensive setups	Safety metrics ↑
33	Kim & Lee (2023)	Embedded NP wheel	Grinding (steel)	Advanced	Wheel released NPs; Ra ↓ 35%.	Durability concerns	Ra ↓, Tool life ↑
34	Zhao et al. (2024)	Smart NF	Lab-scale adaptive lubrication	Advanced	Viscosity tuned via electric fields.	Lab scale only	Adaptive performance
35	Vidyasagar et al. (2024)	—	AI monitoring of NF sump	Advanced	Detected nanoparticle aggregation in real-time.	Accuracy with opaque fluids	Process reliability ↑
36	Ibrahim et al. (2024)	Al_2O_3 / Oil | 1 vol.%	Camshaft production (industry)	Oxide NPs	Tool cost ↓ 20%, tool life ↑.	Sponsor-related bias	Tool life ↑, Cost ↓
37	Chen et al. (2024)	NF + laser assist	Grinding (superalloys)	Advanced	MRR ↑ 50%, surface finish improved.	High energy demand	MRR ↑, Ra ↓
38	Silva et al. (2025)	—	Nanofluid recycling study	Eco-Friendly	70% NPs recovered, with 15% loss in performance.	Less than full recovery	Sustainability ↑
39	Nguyen et al. (2025)	—	ISO-protocol proposal	Review	Proposed standardized NF evaluation protocols.	Adoption pending	Benchmarking ↑
40	Ahamed et al. (2025)	Seaweed + clay nanotubes / Bio-oil |0.5 vol.%	Turning (steel)	Eco-Friendly	Biodegradable NF, Ra ↓ 25%.	Scalability issues	Sustainability ↑, Ra ↓

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