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RESEARCH

Tribology in the Era of Industry 5.0: Challenges, Opportunities, and the Road Ahead for Indian Manufacturing

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A B S T R A C T

The transition from Industry 4.0 to Industry 5.0 marks a decisive shift in the global manufacturing paradigm — from hyper-automation toward a framework that foregrounds human centricity, ecological resilience, and sustainable production. Within this evolving landscape, tribology — the science governing friction, wear, and lubrication at contacting surfaces — emerges not merely as a supporting discipline but as a foundational enabler. This review critically synthesises recent literature (2020–2025, with emphasis on publications from 2023 onwards) on the multidimensional role of industrial tribology in advancing India's Industry 5.0 ambitions. Key contributions include: (i) a systematic mapping of nano-enhanced lubrication, bio-lubricants, smart coatings, surface texturing, digital condition monitoring, and sustainable machining against India's industrial landscape; (ii) a critical assessment of scalability, cost-effectiveness, and regulatory frameworks for green tribology in the Indian context; (iii) identification of persistent barriers to technology adoption, particularly for SMEs; and (iv) a proposed Tribology 5.0 framework with specific policy recommendations and industry–academia collaboration models. Quantitative evidence indicates that comprehensive tribological improvements could reduce India's industrial energy losses equivalent to 1.0–1.4% of GDP annually. This corresponds, as an illustrative order-of-magnitude extrapolation rather than an independently validated estimate, to approximately USD 37–52 billion at 2024 GDP. This underscores the strategic and economic significance of tribological investment.

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1. INTRODUCTION

There is a recurring tendency in engineering discourse to treat tribology as a solved problem — as something adequately addressed by selecting the right lubricant grade from a manufacturer's catalogue. This perception is not merely incomplete; in the context of modern industrial demands, it is actively counterproductive. Holmberg and Erdemir [1] demonstrated that tribological phenomena remain an active research frontier, with friction and wear losses costing the global economy

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approximately 1.4% of GDP annually — a figure that refutes any notion of a solved discipline. Sinha [2] documents persistent gaps in tribological technology adoption,while Ghobakhloo et al. [3] show that transitions to sustainable, next-generation industrial paradigms depend on coordinated technological, organisational, and policy-level enablers. At its core, tribology encompasses the science and technology of interacting surfaces in relative motion, and its consequences ripple through every domain of mechanical engineering, from microscale bearing contacts in precision instruments to the massive thrust bearings of hydroelectric turbines. The economic significance of tribological phenomena is considerable: authoritative estimates consistently suggest that roughly one-third of all energy consumed by industry is dissipated through friction, and wear-related material losses account for an enormous proportion of component replacement costs worldwide [1].

India, as one of the world's fastest-growing major economies and a country with declared ambitions to emerge as a global manufacturing hub, cannot afford to treat tribology as peripheral. The nation's industrial infrastructure — spanning automotive, textiles, mining, steel, chemical processing, and power generation — collectively operates hundreds of millions of moving interfaces every hour. The inefficiencies embedded in these interfaces, accumulated across decades of under-investment in tribological awareness, translate into vast quantities of wasted energy, premature machinery failure, and unnecessary environmental burden.

The emergence of Industry 5.0 as a framework for the next phase of industrial development introduces a new set of expectations that tribology must meet. Unlike its predecessor Industry 4.0, which centred primarily on automation, cyber-physical integration, and data-driven production, Industry 5.0 explicitly incorporates three foundational pillars: human centricity, sustainability, and resilience [4]. These pillars reframe tribological challenges in an important way. Green lubrication, biodegradable formulations, and energy-efficient surface engineering are no longer optional improvements — they are prerequisites of sustainable industrial operation. Meanwhile, the human centricity dimension calls for intelligent systems that assist workers in making tribological decisions rather than displacing them entirely.

India presents a uniquely complex canvas for this transformation. The country's industrial base is heterogeneous, ranging from world-class automotive OEMs with sophisticated tribological practices to small and medium enterprises (SMEs) that still rely on conventional mineral oils applied through largely manual lubrication routines. Bridging this gap — technically, economically, and institutionally — is perhaps the defining tribological challenge of the coming decade.

This review undertakes a critical examination of the intersection between industrial tribology and Industry 5.0, with particular attention to the Indian context. Drawing on peer-reviewed literature published primarily from 2023 onwards, the paper synthesises emerging findings across nano-enhanced lubrication, intelligent tribological monitoring, surface engineering, and green tribology. It proceeds to map these findings against the structure of India's industrial landscape, identify research gaps, and propose an integrated framework for tribology in the Industry 5.0 era.

Review Methodology: Literature was identified through systematic searches of Scopus, Web of Science, and Google Scholar using Boolean search strings combining: 'tribology', 'Industry 5.0', 'Indian manufacturing', 'nano-lubricant', 'bio-lubricant', 'machining tribology', 'predictive maintenance', 'surface coating', and 'digital twin'. The temporal scope was set to 2020–2025, with priority given to publications from 2023 onwards; seminal earlier works were included where foundational context required it. Inclusion criteria required that studies (a) address tribological phenomena in a manufacturing, materials, or lubrication context; and (b) are either conducted in India or directly applicable to the Indian industrial context. Conference proceedings (STLE, TSI), industry reports, and government policy documents supplemented peer-reviewed findings. Exclusion criteria: non-English language; pre-2015 unless frequently cited in recent literature; biomedical-only tribology.

Novelty and Scientific Contribution: The novelty of this review resides in three dimensions. First, this is the first systematic mapping of the full tribological research landscape — lubrication, coatings, machining, and digital monitoring — against the specifically defined three-pillar structure of Industry 5.0 (human-centricity,

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sustainability, resilience) as articulated by the European Commission [4]. Second, the India-specific contextualisation itself constitutes a contribution: existing global tribology reviews treat developing-economy manufacturing generically, whereas this paper examines India's particular industrial configuration, resource endowments, regulatory environment, and institutional landscape to derive actionable, India-relevant recommendations. Third, the Tribology 5.0 framework (Section 10) with its specific policy mechanisms provides a structured translational pathway from research to practice — a contribution absent from previous Indian tribology surveys [2].

2. CONCEPTUAL FRAMEWORK: TRIBOLOGY MEETS INDUSTRY 5.0

2.1 The three pillars of Industry 5.0 and their tribological relevance

The European Commission's landmark 2021 report formally articulated Industry 5.0 as a vision that moves beyond efficiency and productivity to address broader societal goals [4]. The three core axes — human centricity, sustainability, and resilience — each carry direct implications for how tribological science and practice must evolve.

Human centricity demands that technological systems remain intelligible and controllable by skilled human operators. In the tribological domain, this translates into demand for intuitive condition monitoring interfaces, collaborative robots (cobots) equipped with self-lubricating joints, and training systems that enable maintenance personnel to interpret tribological data without requiring specialist expertise. The emergence of augmented reality-assisted maintenance, in which a technician views real-time lubricant condition data overlaid on physical machinery through a wearable display, is a prime example of human-centric tribology in practice [5].

Sustainability is the pillar that most directly reshapes lubrication science. The global lubricant market remains overwhelmingly dependent on petroleum-derived mineral oils, which are non-renewable, poorly biodegradable, and toxic to aquatic ecosystems upon accidental discharge. The imperative to transition to bio-based, biodegradable alternatives is no longer driven purely by scientific curiosity — it is increasingly codified in regulation and anchored in corporate sustainability commitments. Recent research has documented compelling tribological performance from bio-lubricants derived from non-edible vegetable oils such as jatropha, mahua, and neem, which are available in abundance in India [6]. When these biolubricants are enhanced with carefully dispersed nano-additives, their performance can match or surpass that of conventional formulations under specific operating conditions.

Resilience refers to the capacity of industrial systems to absorb disruptions and recover quickly. From a tribological standpoint, resilience is closely connected to predictive maintenance — the ability to detect tribological degradation (abnormal wear, lubricant contamination, seal failure) before it leads to catastrophic breakdown. The COVID-19 pandemic underscored the vulnerability of manufacturing supply chains to disruption, reinforcing the value of condition monitoring systems that can operate remotely and provide early warning of imminent tribological failure.

2.2 Positioning India within the Industry 5.0 transition

India's engagement with Industry 5.0 is shaped by the particular circumstances of its industrial development. Several major automotive manufacturers — Tata Motors, Mahindra, Maruti Suzuki, and the Indian subsidiaries of Bosch, SKF, and Timken — operate at tribological standards broadly comparable to global benchmarks. However, these islands of best practice exist within a broader industrial ecosystem in which SMEs dominate by count, and where tribological awareness remains limited [7].

The Make in India initiative, launched in 2014 and substantially expanded in subsequent years, has accelerated investment in sectors like defence manufacturing, electronics, aerospace, and speciality chemicals — all of which impose demanding tribological requirements. The Production Linked Incentive (PLI) schemes, covering fourteen manufacturing sectors as of

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2024, are creating new impetus for quality and efficiency improvements that tribology is positioned to support.

India's diverse geography also presents a tribological challenge that is frequently overlooked: the country's climatic diversity — from the high humidity of coastal Maharashtra and Bengal to the extreme aridity of Rajasthan, and from tropical temperatures in Tamil Nadu to sub-zero conditions in Himalayan industrial installations — creates a demanding range of operating environments for lubricants and bearing systems. A lubricant formulation developed for temperate European conditions may perform poorly in Indian field applications, highlighting the need for India-specific tribological research and product development.

Figure 1 illustrates the conceptual convergence of tribological science with the three pillars of Industry 5.0, as contextualised for the Indian manufacturing ecosystem.

Fig. 1. Schematic depicting the convergence of tribological domains with the three pillars of Industry 5.0 as applied to major Indian manufacturing sectors.

3. STATE OF TRIBOLOGICAL RESEARCH IN INDIA

3.1 Institutional and academic landscape

India's tribological research community has grown substantially over the past two decades, anchored by premier institutions including IIT Delhi, IIT Madras, IIT Roorkee, IISc Bangalore, NIT Surathkal, NIT Srinagar, and several National Laboratories of the CSIR. The Tribology Society of India (TSI), founded in 1989 and affiliated with the International Tribology Council, organises the biennial IndiaTrib and TriboIndia series of conferences, which have become important platforms for knowledge exchange between academia, industry, and government research bodies [8]. The TriboIndia 2023 conference at NIT Srinagar, for instance, attracted over 250 abstract submissions from more than fifteen countries, with selected papers published in Tribology International and Tribology in Industry, evidencing the growing international visibility of Indian tribological scholarship [8].

A bibliometric survey of Scopus-indexed publications from India in the field of tribology reveals a consistent upward trend, with notable concentrations in the sub-fields of coating tribology, lubrication (including bio-lubricants), biotribology, and machining tribology [2]. The IndiaTrib 2024 conference in Kolkata adopted "Tribology for Sustainable Growth" as its theme — a choice that signals the community's conscious alignment with the sustainability imperatives of the Industry 5.0 era.

3.2 Key research domains

Indian tribological research has diversified considerably. Five broad domains merit particular attention in the context of Industry 5.0: (i) nano-enhanced lubrication, (ii) bio-based and green lubricants, (iii) surface coatings and texture engineering, (iv) machining tribology under sustainable conditions, and (v) condition monitoring and predictive tribology.

4. NANO-ENHANCED LUBRICATION: PROGRESS AND PROSPECTS

The incorporation of nanoscale particles into lubricant base oils has emerged as one of the most active research frontiers in tribology over the past decade, and Indian institutions have contributed

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meaningfully to this area. The fundamental mechanism by which nano-additives improve tribological performance is multifaceted: nanoparticles with appropriate surface chemistry form a thin, protective tribofilm on metallic contact surfaces, thereby increasing the load-carrying capacity of the lubricant film and suppressing both adhesive and abrasive wear. Additionally, spherical nanoparticles can act as "nano-ball bearings," rolling between opposing surfaces and substituting sliding friction with rolling friction [9].

Metal oxide nanoparticles — particularly ZnO, Al_2O_3, CuO, TiO_2, and ZrO_2 — have been extensively investigated as additives in both conventional and bio-based lubricant formulations. A comprehensive review published in 2024 established that oxide nanoparticles at optimal concentrations (typically 0.1–0.5 wt%) consistently deliver measurable reductions in both friction coefficient and specific wear rate across a range of base oil types [9]. Graphene and its derivatives (graphene oxide and reduced graphene oxide) have attracted particular attention due to graphene's exceptional in-plane mechanical strength, lamellar structure, and ability to form self-replenishing tribofilms. Research at Indian institutions has documented friction coefficient reductions of 15–40% and wear rate reductions of 20–60% upon addition of graphene-based nanomaterials to lubricant formulations, depending on concentration, base oil type, and contact conditions [10].

A persistent challenge with nano-enhanced lubricants is dispersion stability — the tendency of nanoparticles to agglomerate over time, which degrades tribological performance and may exacerbate wear by introducing abrasive aggregates into the contact zone. Surfactant-assisted stabilisation and surface functionalisation of nanoparticles are active areas of research aimed at extending shelf life and maintaining colloidal stability under field conditions.

From an industrial application standpoint, dispersion stability translates into concerns about product shelf life, batch-to-batch consistency, and in-service reliability — barriers that have hindered commercial scale-up of nano-lubricants beyond laboratory settings. Studies have documented that even well-dispersed nano-lubricant samples can exhibit significant sedimentation within 48–72 hours of preparation without adequate stabilisation [9]. For Indian SMEs, which often purchase lubricants in bulk and store them for extended periods under variable temperature and humidity conditions, this instability represents a significant practical barrier to adoption. Surfactant selection can substantially influence nanoparticle dispersion stability and tribological performance in vegetable-oil-based nanofluids, indicating that formulation-specific dispersion strategies are important for reliable nanolubricant performance [11].

Table 1. Tribological performance of selected nano-additive systems (2023–2024).

Nano-Additive	Base Oil	Concentration	Friction Reduction (%)	Wear Rate Reduction (%)	Key Finding	Reference
ZnO nanoparticles	Mahua biolubricant	0.3 wt%	22–28	30–38	Improved thermal stability; lower pour point	[9]
Al_2O_3 nanoparticles	Castor oil ester	0.5 wt%	18–25	28–35	Tribofilm formation confirmed by SEM	[9]
Graphene oxide (GO)	Jatropha oil	0.1 wt%	32–40	45–58	Self-replenishing lamellar tribofilm	[10]

The relevance of nano-lubrication to Industry 5.0 sustainability goals is direct: if nano-additives can enable the same or better tribological performance with a smaller volume of lubricant, they support the broader agenda of reducing lubricant consumption, extending drain intervals, and lowering the environmental footprint of industrial lubrication. Table 1 summarises the tribological performance of selected nano-additive systems studied in recent Indian and India-relevant research.

5. GREEN TRIBOLOGY AND BIO-LUBRICANTS: AN INDIAN PERSPECTIVE

5.1 Rationale and resource base

The global lubricant market is estimated to consume approximately 40 million tonnes of oil per year, of which roughly 50% is eventually released into the environment through leakage, volatilisation, or improper disposal [1]. In the Indian context — where rivers, groundwater

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resources, and coastal ecosystems face combined pressure from industrial and agricultural pollution — the transition to biodegradable lubricants carries ecological urgency that extends well beyond regulatory compliance.

India possesses an exceptional natural endowment for bio-lubricant feedstock development. Non-edible vegetable oils derived from jatropha (Jatropha curcas), mahua (Madhuca indica), neem (Azadirachta indica), karanja (Pongamia pinnata), and castor (Ricinus communis) are available in substantial quantities, and their cultivation can be integrated with wasteland development programmes and rural livelihood initiatives — an alignment with the human-centric dimension of Industry 5.0 that is rarely highlighted. Castor oil is a promising biolubricant feedstock because of its high ricinoleic-acid content and distinctive physicochemical and lubricating properties; chemical modification can further improve properties such as oxidation stability, low-temperature behaviour and thermal performance [12].

5.2 Chemical modification strategies

The primary limitations of vegetable oil-based lubricants — poor oxidative and thermal stability, high pour point, and susceptibility to hydrolysis — can be substantially mitigated through chemical modification. Epoxidation, transesterification to yield polyol esters, and acetylation are among the most widely studied modification routes [13].

The STLE's 2023 Emerging Issues and Trends report identified sustainability as the most significantly accelerating theme in tribology and lubrication engineering, with the convergence of bio-based formulations and nano-enhancement representing the frontier of practical implementation [14]. For India, where both the agrarian resource base for bio-feedstock and the research infrastructure to develop formulations are present, this confluence represents a genuine competitive opportunity.

5.3 Scalability, cost-effectiveness, and regulatory frameworks for green tribology in India

While the scientific case for green tribology is well established, its transition from laboratory promise to industrial-scale deployment in India involves significant challenges in scalability, cost-effectiveness, and regulatory alignment. On scalability: jatropha-derived bio-lubricants require dedicated feedstock cultivation and refining infrastructure not yet available at commercial volumes. The National Biofuel Policy (2018, revised 2022) promotes non-edible oilseed cultivation but lacks direct bio-lubricant provisions [14]. A dedicated bio-lubricant development strand within the National Manufacturing Policy would create the supply-side incentives needed for commercial scale-up.

Cost-effectiveness is the most critical barrier for Indian SMEs. Bio-lubricants are currently priced 20–40% above equivalent-grade mineral lubricants in domestic markets — a premium that cost-sensitive operators cannot easily absorb without clearly communicated lifecycle savings. The total cost of ownership argument (extended drain intervals, reduced component wear, avoided disposal costs) typically favours green formulations over a 3–5 year horizon, but requires financial planning capacity often absent at the SME level. Structured instruments — SIDBI energy efficiency loans or BEE-PAT scheme extensions — could bridge this gap [15].

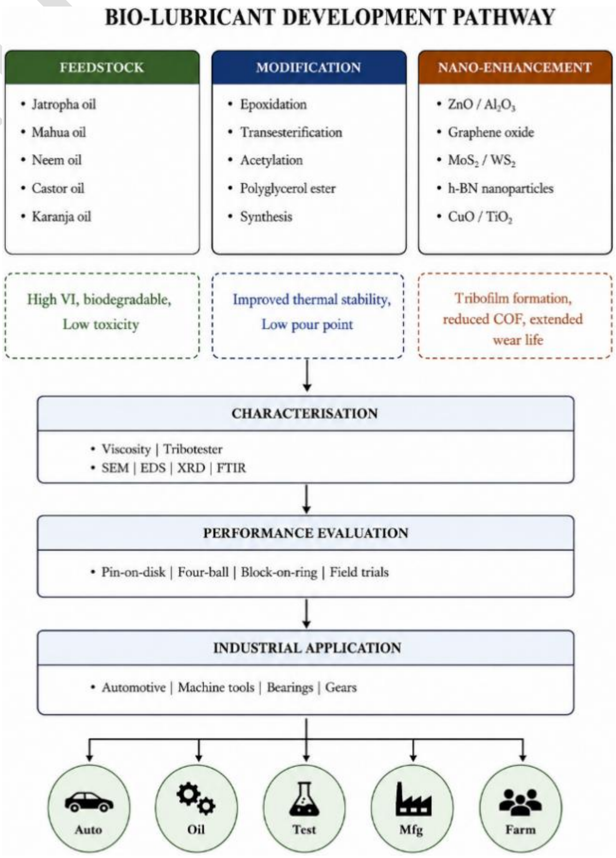

Fig. 2. Schematic of the bio-lubricant development pathway, from indigenous vegetable oil feedstocks through chemical modification and nanoparticle enhancement to industrial deployment.

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At the international level, the EU Ecolabel provides an established environmental labelling framework for lubricants, incorporating criteria related to biodegradability, bioaccumulation, hazardous substances, renewable ingredients and product performance [16]. India could consider developing an equivalent voluntary environmental-labelling framework for industrial lubricants, with criteria adapted to national regulatory and industrial conditions [16].

Figure 2 presents a schematic overview of the bio-lubricant development pathway from vegetable oil feedstock to application-ready formulation, illustrating the key processing and modification stages.

6. SURFACE ENGINEERING FOR INDUSTRY 5.0: COATINGS AND TEXTURING

6.1 Advanced coating technologies

Surface coatings represent one of the most effective tools available for managing tribological performance, particularly in applications where bulk material properties are secondary to interfacial behaviour. In the Industry 5.0 context, the development of smart, multifunctional coatings — those capable of responding to changes in operating conditions, self-healing, or providing real-time tribological information — marks the frontier of surface engineering.

Diamond-like carbon (DLC) coatings, which combine exceptional hardness with low friction coefficients in the range of 0.05–0.15 under boundary lubrication conditions, have seen increasing industrial application in India's automotive sector. Hard anodised and thermal spray coatings are widely used in heavy engineering. Fretting wear protection — a particular challenge in aerospace and defence components that experience small-amplitude oscillatory motion at contact interfaces — has been studied in the context of titanium alloys with DLC and hydroxyapatite coatings at Indian institutions, with fretting wear scar volumes showing significant reductions under optimised coating conditions [2].

The integration of graphene oxide into multilayer coatings has demonstrated particular promise for hydrogen energy applications — a domain of increasing interest in India's energy transition — where conventional lubricants decompose rapidly and DLC coatings can fail by delamination [7].

6.2 Surface texturing

Surface texturing — the deliberate introduction of micro-scale features (dimples, grooves, chevrons) onto bearing and tribological surfaces — has emerged as a powerful complementary strategy to lubrication. Textured surfaces can act as micro-reservoirs for lubricant, trap wear debris to prevent third-body abrasion, and generate hydrodynamic pressure under sliding conditions.

Table 2. Surface modification techniques — comparison of key parameters for industrial tribology.

Technique	Primary Benefit	Friction Reduction	Wear Resistance	Cost	Indian Industry Readiness	Key Applications
DLC coating	Low friction, high hardness	High (COF: 0.05–0.15)	Excellent	High	Moderate (automotive OEMs)	Engines, gears, cutting tools
Thermal spray (HVOF)	Corrosion+wear resistance	Moderate	Very Good	Moderate	High (power, mining)	Boiler tubes, pump impellers
Nitriding/carburising	Enhanced surface hardness	Moderate	Good	Low-Moderate	High (SMEs, gear mfg.)	Gears, shafts, dies
Surface texturing	Hydrodynamic lift, lubricant retention	High (20–40%)	Good	Low-Moderate	Growing (tool industry)	Bearings, cylinder liners, seals
Nanocomposite coatings	Multi-functional protection	High	Excellent	High	Low (R&D stage in India)	Aerospace, defence, precision mfg.
Electroless Ni-P	Uniform coverage, hardness	Moderate	Good	Low	High (general engineering)	Chemical equipment, pumps

Sources: The friction reduction reported for surface texturing (20–40%) is based on [17]. All other entries, including the assessments of Indian industry readiness, represent the authors' qualitative synthesis informed by the background literature and industrial surveys [2,8]. COF = coefficient of friction.

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A 2023 review documented consistent reductions in friction coefficient of 20–40% achievable through optimal texture geometry across a range of contact conditions [17]. Indian researchers at institutions including IIT Delhi, IIT Madras, and NIT Trichy have contributed substantially to understanding the parametric relationships between texture geometry and tribological response under mixed and boundary lubrication conditions.

Table 2 provides a comparative overview of surface modification techniques relevant to Indian industrial applications.

7. DIGITAL TRIBOLOGY: AI, IOT, AND PREDICTIVE MAINTENANCE

7.1 The intelligence layer in tribological systems

Among the transformations that Industry 5.0 brings to manufacturing, the integration of machine learning and artificial intelligence into tribological practice is perhaps the most disruptive. For decades, lubrication management was largely reactive: lubricants were changed on fixed schedules, bearings were replaced only when noise or vibration became audible, and wear was assessed after disassembly. This paradigm is fundamentally inadequate in the context of smart manufacturing, where unplanned downtime carries enormous cost and where the ability to predict maintenance needs based on real-time data is an operational imperative.

The machine learning approach to tribological prediction operates on the principle that tribological state — the instantaneous condition of lubricant films, surface integrity, and contact stress — can be inferred from measurable signals including vibration spectra, acoustic emissions, oil contamination data (particle counts, viscosity changes), temperature profiles, and electrical resistance across contact zones [18]. By training algorithms on large datasets of historical tribological performance, it becomes possible to build predictive models that flag abnormal conditions before they develop into failures.

A 2023 special issue of Lubricants journal specifically highlighted physics-informed machine learning as an emerging trend in tribology, noting that models that embed domain knowledge of contact mechanics and hydrodynamic lubrication theory into their architecture outperform purely data-driven approaches in terms of generalisation beyond the training dataset [18,19]. For India, where many industrial environments produce noisy, incomplete data streams, the ability to incorporate physical priors is particularly valuable.

7.2 Digital twins in tribological systems

The digital twin concept — maintaining a continuously updated virtual model of a physical system — is finding specific application in bearing and gear tribology. Digital-twin approaches are increasingly being investigated for bearing condition monitoring by coupling a virtual bearing model with information obtained from the physical system, enabling degradation and fault states to be assessed from measured response data [20]. Major Indian industry players in steel, power generation, and cement manufacturing — sectors with high tribological consequence and significant downtime costs — are beginning to pilot such systems, often in partnership with global technology vendors.

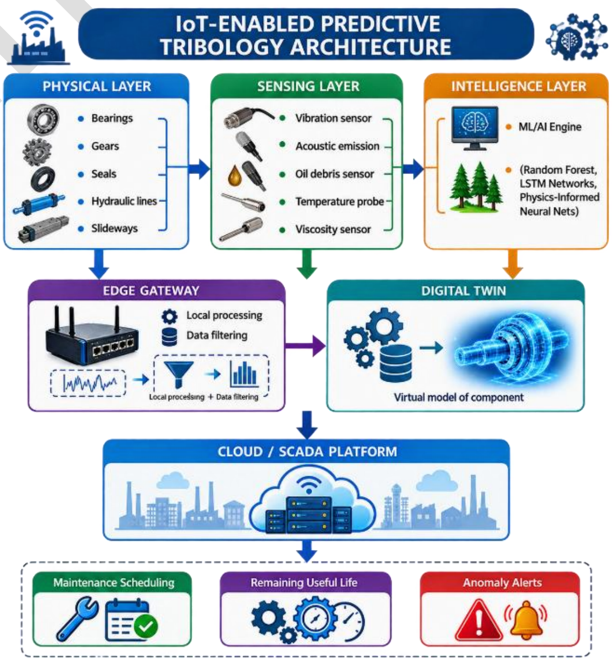

Fig. 3. Architecture of IoT-enabled predictive tribological monitoring integrating physical sensors, edge computing, digital twin modelling, and cloud-based decision support.

The Internet of Things (IoT) provides the data infrastructure that makes digital tribological twins operationally practical. Vibration sensors monitor rotating machinery to detect imbalances,

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misalignment, or bearing faults; temperature sensors identify overheating and lubrication failures; and oil analysis sensors provide continuous visibility into lubricant condition [14,21]. The convergence of these data streams, processed through edge computing systems capable of operating in environments with limited cloud connectivity, is making smart tribological management accessible even in remote industrial installations.

Figure 3 presents a schematic of the digital tribological monitoring architecture applicable to an Indian manufacturing context.

7.3 AI applications in lubricant development

Machine learning is also reshaping the upstream process of lubricant formulation. Traditionally, the development of a new lubricant formulation required extensive experimental iteration — a time-consuming and expensive process. AI-driven approaches allow researchers to build predictive models that map formulation variables (base oil type, additive concentrations, blending ratios) to tribological outcomes, dramatically accelerating the discovery of optimal formulations. Studies published in Lubricants (2023) demonstrated that artificial neural networks could predict friction coefficient and wear rate of nano-lubricant formulations with mean absolute errors below 5%, enabling virtual screening of formulations before physical synthesis [18,22].

For Indian lubricant manufacturers — several of whom, including Indian Oil Corporation R&D and Castrol India, maintain active research programmes — these AI tools offer a pathway to faster innovation cycles and more targeted product development for India-specific applications.

It must be acknowledged that documented case studies of AI-driven tribological solutions deployed specifically within Indian industrial facilities remain limited in the peer-reviewed literature — a gap this review explicitly flags.

8. MACHINING TRIBOLOGY AND SUSTAINABLE MANUFACTURING

8.1 Machining tribology: Scale and strategic importance for India

India's machining sector deserves particular attention in any tribological review — not merely as an application domain but as a strategic priority. The machine tool industry recorded a production value of approximately USD 1.7 billion in 2023–24, with an installed base exceeding 5 million metal-cutting and metal-forming machines across automotive, aerospace, defence, and general engineering clusters [2]. Auto component manufacturers in Pune, Hosur, and Chennai; precision engineering clusters in Coimbatore; and defence toolrooms in Hyderabad and Bengaluru collectively perform hundreds of millions of machining operations annually. Tribological conditions at the cutting tool–workpiece interface — contact pressures of 1–3 GPa, flash temperatures of 600–1000°C, and strain rates approaching 10^6 s^{-1} — are among the most extreme encountered in any tribological application and directly govern tool life, surface integrity, dimensional accuracy, and energy consumption [23,24].

The health and environmental consequences of conventional flood cooling are acute in Indian industrial clusters. Metalworking fluid (MWF) mist inhalation is associated with occupational respiratory disease documented in automotive cluster workers. MWF disposal into municipal drainage — illegal under the Hazardous and Other Wastes (Management and Transboundary Movement) Rules 2016 (Schedule I classification) — is nonetheless widespread among smaller machining shops lacking treatment infrastructure. These regulatory and economic pressures make dry, MQL, and cryogenic machining compelling as practical risk-mitigation strategies, not merely futuristic aspirations [24].

Recent research on EN-31 steel has demonstrated the potential of minimum quantity lubrication (MQL) to control tool flank wear and cutting temperature. Sharma et al. reported an optimized MQL condition for face milling of EN-31 and observed a 2.10% reduction in flank wear at the optimum parameter combination [24]. Hybrid cryogenic–MQL (CryoMQL) machining of Inconel 718 has demonstrated substantial machinability improvements; Shokrani et al. reported a tool life of 523 s under CryoMQL compared with 283 s under MQL and 198 s under cryogenic cooling alone, corresponding to an almost twofold improvement over MQL [25]. These findings are directly actionable for Indian manufacturers and warrant integration into sector-specific guidelines developed by AIFI and IMTMA.

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8.2 Minimum quantity lubrication and solid lubricants

Machining tribology encompasses the study of friction, wear, and lubrication at the cutting tool–workpiece interface. The transition to sustainable machining alternatives is driven by the health, environmental, and regulatory pressures outlined in Section 8.1.

Minimum Quantity Lubrication (MQL), in which a small, precisely metered volume of lubricant (typically 10–200 mL/hour) is delivered directly to the cutting zone in the form of an aerosol, has emerged as a compelling sustainable alternative. When MQL is combined with vegetable oil–based fluids, the combination achieves the dual goal of reducing fluid consumption and replacing petroleum-derived cutting fluids with biodegradable alternatives. Recent work on milling of AISI 52100 steel using MoS_2 and composite MoS_2–TiO_2 solid lubricants in MQL mode demonstrated measurable reductions in cutting zone temperature and improved tool life relative to dry machining, establishing solid lubricant–assisted MQL as a viable sustainable machining strategy [23].

Cryogenic cooling — the application of liquid nitrogen (LN_2) or supercritical CO_2 to the cutting zone — is another sustainable strategy gaining traction for machining of difficult-to-cut materials such as titanium alloys and nickel superalloys, which are increasing in use in India's growing aerospace and defence sectors. Published results from 2023 documented that cryogenic cooling of AA2024-T351 aluminium alloy machining produced superior tool life and tribological characteristics relative to dry and MQL conditions [26].

8.3 Industry-specific tribological challenges in India

Table 3 maps tribological challenges across major Indian industrial sectors and identifies the Industry 5.0–aligned solutions being pursued or warranted.

Table 3. Tribological challenges and Industry 5.0–aligned solutions across major Indian industrial sectors.

Sector	Primary Tribological Challenge	Economic Impact	Current Approach	Industry 5.0–Aligned Solution
Automotive	Engine wear, gear & bearing friction, tyre tribology	High; directly affects fuel economy	Conventional mineral oils with ZnDTP additives	EV-compatible lubricants; AI-optimised viscosity management; DLC-coated engine components
Steel & Metals	Abrasive wear in rolling mills, erosion in conveyors	Very High; production continuity critical	Hard surfacing, chromium carbide coatings	HVOF nanocomposite coatings; IoT-based mill roll condition monitoring
Textile	Spindle bearing wear, yarn friction in guides	Moderate; affects yarn quality	Periodic manual lubrication	Automatic lubrication systems; smart bearing sensors
Mining	Abrasive-erosive wear of crushers, conveyors, slurry pumps	Very High; component life critical	Replacement-focused maintenance	Predictive wear monitoring; nano-composite wear-resistant liners
Power Generation	Turbine bearing degradation, boiler tube erosion	Very High; grid reliability impact	Periodic inspection; conventional lubricants	Digital twin–based bearing health monitoring; tribo-corrosion-resistant coatings
Defence & Aerospace	Fretting wear, extreme condition tribology	Critical; safety and reliability	Speciality greases; periodic overhaul	Self-lubricating coatings; real-time sensor-based condition assessment

Sources: Contextual background was drawn from [1,2,7,8,14]. The sector–technique pairings and Economic Impact classifications (Moderate/High/Very High/Critical) represent the authors' qualitative synthesis and are not derived from numerical results reported in any single study.

9. BARRIERS TO TRIBOLOGICAL ADVANCEMENT IN INDIAN INDUSTRY

Despite the substantial and growing body of research, the translation of tribological advances into widespread industrial practice in India faces persistent obstacles. Understanding these barriers is essential for designing effective interventions.

Technology awareness and diffusion remain the most fundamental challenge. A 2024 assessment of India's tribological research landscape noted

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that while publications from premier institutions are internationally competitive, industrial uptake of even well-established tribological practices — such as regular oil analysis, tribologically informed lubrication interval management, and proper lubricant selection matching machinery requirements — lags significantly, particularly among SMEs [2]. The gap between research output and industrial practice thus remains considerable.

Economic constraints shape decision-making at the plant level in important ways. For an SME operator working on tight margins, the upfront cost of deploying smart lubrication management systems, sensor arrays, or premium nano-lubricant formulations is difficult to justify through operational cost savings that may only materialise over several years. The absence of readily accessible financing or subsidy mechanisms for industrial energy efficiency investments compounds this challenge.

Supply chain and formulation infrastructure represent a third barrier. Even where awareness and willingness to adopt exist, the availability of high-quality bio-lubricant formulations meeting industry specifications — available in appropriate grades, certified for specific applications, and supported by technical service — is limited in India compared to developed markets. Domestic lubricant blending capabilities are growing, led by public sector enterprises like Indian Oil, HPCL, and BPCL, but the speciality segment remains underdeveloped.

Skill and human capital gaps in tribological disciplines affect both shopfloor maintenance practice and R&D capability. Engineering curricula at many institutions treat tribology as a minor ancillary topic within machine design courses, rather than as a discipline warranting dedicated instruction. The Tribology Society of India's annual Summer School in Tribology addresses this gap to some extent, but the scale of intervention remains modest relative to the need.

10. PROPOSED FRAMEWORK: TRIBOLOGY 5.0 FOR INDIA

Sections 3–11 collectively constitute a diagnostic — identifying what is known, what is being done, and where the gaps lie. Section 10 fulfils the constructive, prescriptive function expected of a policy-oriented review. Without it, the review would satisfy a descriptive mandate but fail the translational mandate implicit in its title ('the Road Ahead'). Section 10 operationalises the three Industry 5.0 pillars from Section 2 into actionable framework pillars for India — completing a circular structure: Framework (Section 2) → Evidence (Sections 3–9) → Operationalisation (Section 10).

Drawing on the foregoing analysis, this paper proposes a framework — termed 'Tribology 5.0 for India' — that charts a coherent path from the current state of industrial practice toward a vision consistent with the ambitions of Industry 5.0. This framework rests on four integrated pillars, as illustrated in Figure 4.

Fig. 4. Proposed Tribology 5.0 framework for Indian manufacturing, structured around four integrated pillars supported by enabling mechanisms.

10.1 Pillar 1: Green lubrication ecosystem

A coherent national strategy for transitioning Indian industry toward bio-based and sustainable lubrication requires coordinated action at multiple levels. At the research level, Indian institutions should prioritise the development of non-edible vegetable oil–based formulations tailored to the specific viscosity, temperature, and additive requirements of high-volume Indian applications — two-wheeler and small commercial vehicle engines, textile spindle bearings, agricultural equipment. At the commercial level, domestic lubricant blenders require support in

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establishing the testing, certification, and quality assurance infrastructure necessary to bring bio-lubricant products to market. At the policy level, procurement mandates for government-operated vehicle fleets and industrial facilities could create the demand signal needed to achieve scale economies in bio-lubricant production [14].

10.2 Pillar 2: Digital tribological intelligence

Smart condition monitoring of tribological systems should be positioned as a core component of India's smart manufacturing programme. The deployment of oil analysis sensors, bearing vibration monitors, and acoustic emission detectors — connected through industrial IoT protocols to central maintenance management platforms — can dramatically reduce unplanned downtime in sectors like steel, cement, and power generation, where a single bearing failure in a critical machine can halt production for days [20]. The development and dissemination of standardised architectures for digital tribological twins would lower the barrier to adoption, particularly for SMEs that cannot afford bespoke digital transformation projects.

10.3 Pillar 3: Surface innovation

A focused national programme to promote the adoption of advanced surface coatings and texturing in Indian manufacturing would yield measurable energy and material savings. Technology demonstrators in automotive component manufacturing, precision tooling, and hydraulic equipment — supported by cost-benefit documentation accessible to industrial decision-makers — would accelerate the spread of DLC, HVOF, and textured surface technologies beyond the current base of large OEM adopters.

10.4 Pillar 4: Human capital

The human centricity dimension of Industry 5.0 demands that tribological competence be embedded much more widely in the Indian engineering workforce. This requires reform of undergraduate mechanical engineering curricula to include dedicated tribology instruction; expansion of industry-facing training programmes through the TSI; and the creation of industry-academia knowledge transfer partnerships that allow practising engineers to access research insights without navigating academic publication barriers [8].

11. ENERGY AND ECONOMIC CASE FOR TRIBOLOGICAL INVESTMENT

A frequently underutilised justification for tribological investment is the quantifiable energy savings achievable through effective friction and wear management. Jost (1966) estimated that the UK alone could save approximately 1% of GDP through improved tribological practices — an estimate that, though dated, has been repeatedly validated in updated form for different national contexts. For India, with a GDP of approximately USD 3.7 trillion in 2024 and an industrial sector consuming roughly 45% of total primary energy, plausible estimates suggest that comprehensive tribological improvements across manufacturing, transportation, and power generation could reduce energy losses equivalent to 1.0–1.4% of GDP annually. This is the authors' own order-of-magnitude extrapolation of the global percentage in [1] to India's GDP, not an independently sourced or officially published Indian estimate, and corresponds to approximately USD 37–52 billion at current valuations.

The STLE's 2023 report reinforced this calculus, identifying tribological applications as having material potential to reduce greenhouse gas emissions across the industrial economy — a conclusion directly relevant to India's commitments under the Paris Agreement and its Nationally Determined Contributions [14]. In this light, tribological investment is not merely an engineering efficiency measure; it is a climate action with economically quantifiable returns.

Table 4 provides a comparative assessment of energy-saving potential from tribological interventions across Indian industrial sectors.

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Table 4. Estimated energy-saving potential from tribological interventions in key Indian industrial sectors.

Sector	Relative Energy Intensity	Estimated Tribological Loss (%)	Indicative Recovery Potential (qualitative)	Priority Interventions
Automotive (OEM + fleet)	High (qualitative)	10–15% through friction	Moderate–High (illustrative)	AI-optimised lubrication; DLC engine coatings
Steel manufacturing	High (qualitative)	8–12% (rolling mill friction)	Moderate (illustrative)	Smart rolling oil management; IoT mill monitoring
Textile industry	Medium (qualitative)	5–8% (spindle/guide friction)	Low–Moderate (illustrative)	Nano-lubricant spindle oils; auto-lubrication systems
Mining & quarrying	Medium (qualitative)	15–20% (abrasive/erosive wear)	Moderate (illustrative)	Wear-resistant liners; predictive crusher maintenance
Power generation	Medium (qualitative)	6–10% (turbine/pump friction)	Low–Moderate (illustrative)	Digital twin bearing monitoring; low-friction seals

Sources and derivation: The ranking is based on aggregate industrial final-energy-consumption shares reported in the IEA World Energy Outlook 2024, India section [27], and the NITI Aayog India Energy Security Scenarios (IESS) 2047 v4.0 sectoral demand tool [28], both used only for broad, directional context. Tribological-loss percentages remain literature-typical ranges consistent with the global estimates in [1], not from a per-sector Indian measurement, and are presented as illustrative rather than measured. Mtoe = Million tonnes of oil equivalent.

12. FUTURE RESEARCH DIRECTIONS

The foregoing review points toward several priority directions for future tribological research in the Indian context.

Formulation of India-specific bio-lubricant grades for automotive, agricultural, and industrial applications represents the most immediately actionable research need. Systematic tribotesting of bio-lubricant formulations derived from domestically abundant non-edible oils, under the specific temperature, load, and contamination conditions prevalent in Indian field applications, would produce the design data needed for industrial adoption.
Development of low-cost, robust tribological sensors suitable for deployment in the harsh environments of Indian manufacturing plants — high temperature, dust, vibration, and humidity — remains a critical gap. Current sensor technologies are largely developed for controlled European or North American conditions, and their reliability in Indian field environments requires systematic evaluation and adaptation.

Physics-informed machine learning models for wear prediction that incorporate both data-driven pattern recognition and mechanistic knowledge of contact mechanics offer the most reliable path to predictive tribological systems. Collaborative research programmes between IITs, NITs, and industrial partners to build and validate such models using real field data would be of high value.

Tribological solutions for electric vehicles (EVs), which are expected to see explosive growth in India through the PM e-DRIVE scheme and FAME initiatives, require specific attention. EV drivetrains impose new tribological requirements on gear lubricants — including compatibility with copper-based electrical components, resistance to degradation by stray electrical currents, and stability at the higher speeds of EV gearboxes — that differ substantially from conventional internal combustion engine requirements [14].

Circular economy approaches to lubricant lifecycle management — including re-refining of used lubricants, development of recyclable lubricant formulations, and systematic tribological analysis to extend drain intervals — align directly with Industry 5.0 sustainability goals and require coordinated development at the national level.

13. CONCLUSIONS

This review has examined the intersection of industrial tribology and Industry 5.0 through the lens of India's manufacturing context, drawing on a body of literature spanning nano-enhanced

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lubrication, bio-based lubricants, smart coatings, surface texturing, digital condition monitoring, and sustainable machining. Several conclusions emerge with clarity.

First, tribology is not a peripheral technical discipline but a central enabler of the sustainability, resilience, and human-centricity goals that define Industry 5.0 [29]. The friction and wear phenomena at industrial contact interfaces translate directly into energy consumption, material loss, maintenance cost, and environmental burden — all of which are measurable, manageable, and improvable through informed tribological practice.

Second, India possesses significant natural and intellectual resources for tribological innovation. The availability of diverse non-edible vegetable oil feedstocks for bio-lubricant development, a growing community of tribological researchers at premier institutions, and a national industrial base that spans sectors of high tribological relevance creates a foundation for meaningful progress. What is required is the translational infrastructure to convert research advances into sustained industrial practice.

Third, the four pillars of the Tribology 5.0 framework — green lubrication, digital tribological intelligence, surface innovation, and human capital — provide an integrated roadmap. Progress on any single pillar is valuable but insufficient; lasting improvement requires coordinated advancement on all four fronts, supported by coherent government policy and institutional commitment.

Fourth, the economic case for tribological investment in India is compelling. Estimated annual energy savings from comprehensive tribological improvements across industry are, on an order-of-magnitude extrapolation from global figures rather than a validated Indian estimate, in the range of USD 37–52 billion. Even treated cautiously, this places tribology alongside energy efficiency and digital transformation as a priority domain for industrial policy attention.

The journey from the present fragmented state of tribological practice across Indian industry to a vision of smart, green, human-centred tribological systems is neither short nor simple. But the direction is clear, the tools are largely available, and the incentives — economic, environmental, and strategic — are formidable. For a nation aspiring to lead the next phase of global manufacturing, advancing tribological capability is not optional. It is foundational.

To translate this vision into action, the authors advance the following specific recommendations:

1. Policy Recommendations: The Ministry of Heavy Industries should establish a dedicated 'Green Tribology Mission' under the National Manufacturing Policy (suggested: INR 500 crore over five years) to support bio-lubricant infrastructure, sensor development, and SME technology adoption. BIS should introduce a voluntary 'Green Lubricant' certification label with mandatory biodegradability and eco-toxicological criteria, with a roadmap to mandatory certification for government procurement within three years. BEE should expand the PAT scheme to include tribological efficiency metrics (friction loss reduction, extended drain intervals, wear-related component life improvement) as quantifiable energy-saving activities eligible for Energy Savings Certificates (ESCerts).
2. Industry–Academia Collaboration Models: The Tribology Society of India, in partnership with CII and sector clusters (ACMA for automotive, IMTMA for machine tools), should establish Tribology Technology Cells — embedded units co-located between industrial partners and research institutions, modelled on the UK's Advanced Propulsion Centre. These cells would conduct application-targeted tribological testing, validate laboratory solutions under real industrial conditions, and publish annual open-access industrial tribology benchmarking reports.
3. Funding Avenues: SERB Core Research Grants and DST Technology Mission Division projects should designate tribology an explicit priority area, with calls targeting EV tribology, bio-lubricant scale-up, and machining of indigenous aerospace alloys. The MSME Credit Linked Capital Subsidy Scheme (CLCSS) should be expanded to cover tribological technology upgrades — smart lubrication systems, MQL units, surface texturing equipment — as eligible capital expenditures for SMEs.

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Limitations: This review has limitations that should be acknowledged: (a) the primary literature base is largely experimental rather than field-based; (b) sectoral energy savings estimates involve extrapolation of global coefficients to Indian conditions and carry inherent uncertainty; (c) AI/digital tribology case studies cited are predominantly from industry reports rather than peer-reviewed sources; (d) the reference count remains below that of an exhaustive systematic review. Future work should prioritise field-based studies, expanded India-specific primary data, and a formal PRISMA-compliant systematic review methodology.

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