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Tribology, Artificial Intelligence, Machine Learning : Multicomponent Interaction (Review)

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Abstract
This article presents a review analysis and develops a process scheme in the field of tribology related to the application and development of artificial intelligence, on the basis of which a systematic approach has been carried out; it clearly demonstrates that one of the fundamental characteristics of tribology is the strong interconnection between different scientific disciplines. The conducted analysis shows that tribology is not only a complex mechanical system but also a research field that inevitably requires interdisciplinary efforts. The study indicates that progress in tribology is increasingly associated with the development of artificial intelligence concepts, machine learning, triboinformatics, and "green" tribology. From this perspective, the article emphasizes that future tribologists should focus on advancing scientific fields such as mechanical engineering, physics, and materials science within the framework of next-generation information and communication technologies. Artificial intelligence (AI) with its advanced machine learning (ML) capabilities and the rapid processing capacity of triboinformatics can help researchers quickly identify valuable patterns, trends, and relationships from subjective and experimental data. Tribological behavior changes over time. It depends on the system and is characterized by complex multidisciplinary interactions. The friction process involves various physical phenomena including: mechanics, thermology, electricity, optics, magnetism, and others. Therefore, tribological data are characterized by complex multicomponent interactions and possess features such as: multidisciplinarity, multilevel structure, and multiscale nature. Considering the emergence of triboinformatics - a new interdisciplinary field formed by the integration of tribology and informatics - this review will expand the future research directions and framework of the concept of "Artificial Intelligence for Tribology." As a result of extensive research, a scientifically substantiated new roadmap (framework) has been developed for the application and advancement of artificial intelligence and machine learning in the field of tribology. By establishing a systematic understanding, it is recommended to enhance the efficiency of solving problems in tribology. Such an approach will enable the application of triboinformatics methods to address common problems such as monitoring tribological behavior, predicting system performance, and optimizing system operation.

Keywords: Tribology, Artificial Intelligence (AI); Machine Learning (ML); "green" tribology; triboinformatics; Artificial Neural Network (ANN).

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The application areas of tribology have expanded across diverse directions, and a considerable number of research studies related to tribological science have been published over the last decade. This review article summarizes and presents to readers the most recent advances achieved in studies conducted over the past four to five years in various aspects of tribology.

The main directions examined in this review include: lubrication, wear and surface engineering, bio tribology, high-temperature tribology, and computational tribology. The article aims not only to highlight recent research findings on these topics but also to provide perspectives on future developments in these fields.

However, it should be noted that this review has certain limitations. One of the most significant limitations arises from the fact that tribology is a highly multidisciplinary and multicomponent field, and research outcomes are widely dispersed across various scientific disciplines. Consequently, some relevant studies may inadvertently have been overlooked.

The system dependence, time-varying nature, and multifaceted interactions inherent in tribological phenomena generate multidimensional and highly complex structured datasets. These characteristics create favorable conditions for the application of artificial intelligence in tribology.

The deep integration of artificial intelligence methods into tribological research provides several important advantages:
- Faster acquisition of knowledge;
- Systematic integration of heterogeneous data;
- Development of predictive behavioral models;
- Early detection and diagnostic capabilities.

For example, artificial intelligence enables the early diagnosis of mechanical failures by establishing relationships between wear processes and various signal sources, including vibration, acoustic emissions, electrical signals, and sound pressure measurements.

Furthermore, the simulation and prediction of tribological behavior under different operating conditions are of considerable importance for the design of more durable and reliable mechanical systems.

Despite these limitations, it is hoped that this review will draw attention to the latest and most significant scientific achievements in tribology and serve as a valuable resource for the rapidly growing tribology research community.

The widespread adoption of next-generation information and communication technologies including: Artificial Intelligence (AI), the Internet of Things (IoT), and Blockchain technology, is accelerating technologically and industrially. In this context, artificial intelligence has attracted substantial interest from governments, industry, academia, and society as a whole.

Purpose of the work

The purpose of this study is to provide a comprehensive review of information and communication technologies, particularly Artificial Intelligence (AI), the Internet of Things (IoT), and Machine Learning (ML), based on the extensive body of published research in the field of tribology. The review presents an overview of the scope of artificial intelligence, the factors underlying its emergence and development, the technologies employed, and its areas of application. Furthermore, logical perspectives concerning the future development of artificial intelligence are discussed.

The review also provides important findings and practical insights for specialists working in the industrial sector. Another contribution of this study is the clear presentation of the current state of the art in artificial intelligence, thereby serving as a valuable reference for future research.

As is well known, friction plays a crucial role in energy dissipation, equipment failure, and even energy supply systems in modern society. Following decades of research, the volume of tribological data and knowledge has continued to increase significantly.

Due to the strong systemic and multidisciplinary nature of tribology, tribological information is dispersed across various scientific fields and exists in different forms, including technical documentation, databases, and scientific publications. Such fragmentation increases information entropy within the system and is not particularly favorable for the preservation, management, and circulation of research knowledge.

With the advancement of computer and information sciences, many disciplines have become integrated with information technologies, leading to the emergence of multidisciplinary informatics-based research domains. In this context, the present work promotes the integration of information technologies with tribological research as well as introduces the concept and architecture of triboinformatics and demonstrates a representative case study illustrating the application of the proposed framework.

The introduction and development of the triboinformatics concept described herein are expected to enhance the efficiency of tribological research and optimize scientific investigation processes, therefore contributing significantly to the advancement of tribological science.

Research in tribology primarily focuses on the process of friction, wear, and lubrication occurring between interacting surfaces. As the level of industrialisation in human society continues to increase, the range of objects and systems investigated within tribology has expanded correspondingly.

The methodologies employed in tribological research have evolved from the empirical science stage (based on observed phenomena), to the theoretical science stage (based on mathematical and physical models), and subsequently to the computational science stage, relying on advanced simulations. Tribology is a strongly engineering-oriented scientific discipline. Owing to its intensive interdisciplinary interactions, it incorporates knowledge from informatics, mathematics, physics, chemistry, materials science, mechanical engineering, and numerous related fields.

The continuous generation of new data and models forms the foundation of progress in tribology. Advances in information technologies have introduced new and more efficient methods for collecting, processing, and analysing tribological data. As a result, the concept of triboinformatics has emerged.

Within the framework of triboinformatics, the application of triboinformatics methods to tribological research is examined, and useful directions are proposed for conducting more efficient and scientifically grounded tribological investigations through the adoption of triboinformatics-based approaches.

For a long time, tribology has remained one of the most important scientific disciplines and continues to influence nearly every aspect of modern life. A deeper understanding of tribological phenomena provides opportunities to address future technological challenges. The achievements attained to date have been built upon numerous precise experimental investigations and an increasing number of sophisticated computer simulations spanning multiple scales and involving several interacting physical domains.

Based on this extensive and valuable knowledge base, advanced methods for data management, analysis, and learning can be developed and applied to further expand existing knowledge. In this regard, modern Machine Learning (ML) and Artificial Intelligence (AI) techniques provide powerful tools for investigating complex processes occurring within tribological systems, enabling their behavior to be efficiently classified and quantitatively evaluated, even in real-time environments. Consequently, the potential of these methods extends beyond academic research and encompasses a broad range of industrial applications.

To establish a roadmap in this rapidly evolving field, recent studies addressing tribological challenges through ML and AI approaches have been systematically reviewed. The focus is placed not only on the development of novel ML and AI methodologies but also on demonstrating potential applications of existing methods and their adaptation to tribological problems.

It should be emphasized that this review is based on the analysis of several publications, including a number of original research articles (Meng et al., 2020; Bhushan & Ko, 2003; Grützmacher et al., 2019; Hinton & Salakhutdinov, 2006; Xu, 2013; Bommasani et al., 2021; Zhang & Lu, 2021; Ramakrishna et al., 2019; Hwang et al., 2018) and a review paper (Zhang et al., 2021). The collected materials were contributed by both academic and industrial researchers from various countries and reflect state-of-the-art investigations in this area. These studies provide valuable insights into the development and application of advanced ML and AI techniques for addressing a wide range of problems related to friction, lubrication, and wear.

Owing to their powerful learning capabilities and rapid data-processing performance, artificial intelligence techniques enable researchers to efficiently identify meaningful patterns, trends, and relationships within large-scale datasets.

Tribological data are inherently multidomain, multilevel, and multidimensional in nature, creating extensive opportunities for the application of artificial intelligence within tribology.

This review identifies the scope, classification, and recent development trends of artificial intelligence applications in tribology and provides a comprehensive analysis of their implementation in the following areas (Yin et al., 2023):

- Fundamental Theories of Tribology
- Intelligent Tribology
- Component Tribology
- Extreme Tribology
- Biotribology
- Green Tribology

In addition, the interdisciplinary field known as triboinformatics - which has emerged through the integration of tribology and informatics - is examined. The review further discusses future research directions and the conceptual framework of the rapidly developing field of "AI for Tribology" (Zhang et al., 2021; Tremmel & Marian, 2022; Haenlein & Kaplan, 2019).

In the article, tribological system (tribosystem) data are classified into several categories (Haenlein & Kaplan, 2019):

1. Input data;
2. Intrinsic (internal) system data;
3. Output data;
4. 4. Tribological condition data;
5. 5. Derived condition data.

Based on these categories of data, an integrated framework combining various artificial intelligence methods, including regression, classification, clustering, and dimensionality reduction, has been proposed. This approach enables triboinformatics methodologies to address the following challenges (Yin et al., 2023; Paturi et al., 2023):

- Tribological condition monitoring;
- Behavior prediction;
- System optimization.

Rosenkranz et al. (2020) highlighted several successful applications of AI methods within the tribological domain. These applications have demonstrated significant potential in areas, such as: online condition monitoring, materials design and composition optimization, lubricant formulation development, as well as the analysis and prediction of lubrication mechanisms and fluid film formation processes (Dai et al., 2006; Shah et al., 2020; Zhang et al., 2022).

Artificial Intelligence (AI) is generally described as "the ability of a system to accurately interpret external information, learn from experience and data, and apply the acquired knowledge through adaptive decision-making processes to accomplish specific objectives and tasks".

As is already well known, conducting experiments and analyzing their results are often time-consuming and costly processes; therefore, modern technologies are increasingly required to reduce both the duration and expense of such activities. In recent years, the application of computer-based approaches to mechanical systems has grown significantly as an effective means of addressing this challenge. One of the most important methods employed in this context is Artificial Neural Networks (ANNs), which have demonstrated considerable effectiveness in reducing the time and cost associated with experimental investigations (Kilic et al., 2022).

This approach has been applied to the study of various tribological characteristics, including the coefficient of friction, wear behavior, lubricant properties, lubricant film thickness formation and the surface and mechanical properties of composite and polymeric materials.

ANN models utilize key performance parameters obtained from experimental studies to predict the performance of a mechanism during the conceptual design stage. Functioning as mathematical tools (inspired by the neural architecture of the human brain), ANNs process input and output data to solve complex engineering and scientific problems. Unlike conventional analytical methods, ANNs possess the capability to predict output responses even from limited input data once the learning process has been completed (Hinton & Salakhutdinov, 2006).

One of the principal advantages of ANNs is their high learning capability and their ability to model multidimensional, nonlinear, and complex functions. The network learns by organizing the experimental data provided to it and identifying the underlying relationships that characterize the problem under investigation. Furthermore, ANNs are relatively insensitive to minor variations in the input data, such as noise, which contributes to improved robustness and error reduction. Recent studies have applied ANN models to pin-on-disk (POD) tests, fretting wear experiments, as well as tensile and compressive strength investigations (Ren et al., 2019; Ma et al., 2022; Liu et al., 2014).

The application of ANNs has played a significant role in the study of various tribological characteristics, including: condition and tool wear monitoring, wear and friction behavior, lubrication processes, lubricant composition optimization, surface modification, and material property evaluation. One of the most important advantages of this approach is its ability to predict future outcomes based on initial experimental data, thereby reducing or even eliminating the need for additional experimental investigations (Ren et al., 2019; Lin et al., 2018; Sieberg et al., 2022; Broitman, 2014).

This capability contributes significantly to reducing the duration of experimental investigations and is considered one of the most promising applications of ANNs. Overall, ANNs serve as powerful simulation tools for tribologists, enabling substantial savings in both time and research resources during tribological investigations (Sattari et al., 2020; Perčić et al., 2021).

The present reviews synthesizes published studies that approach artificial intelligence from different perspectives. These contributions have been presented by leading experts and researchers in the field of artificial intelligence and provide a comprehensive overview of current developments and emerging trends.

We now turn our attention to several perspectives regarding the future development of artificial intelligence.

Artificial intelligence, particularly machine learning techniques, has attracted considerable attention within the tribology community because of its ability to predict tribologically significant parameters such as the coefficient of friction and lubricant film thickness (Sattari et al., 2020; Jaza et al., 2021; Albayrak et al., 2023).

A major focus of recent research has been to highlight the advances achieved through the application of artificial intelligence - particularly artificial neural networks - in tribological investigations. The presentation and discussion of successful case studies demonstrate that these approaches are capable of predicting tribological properties with a high degree of accuracy and efficiency (Partovi et al., 2023; Hasan et al., 2021).

With regard to future research directions and emerging trends, it is expected that the concepts of artificial intelligence and machine learning will be more extensively applied within tribology. Particular attention should be devoted to micro-, meso-, and macro-scale perspectives, including the characterization of evolving surface topography and the design and optimization of lubrication systems, among other areas of tribological significance (Jaza et al., 2021; Kumar et al., 2013). Another important direction is Green Tribology, a branch of tribology that seeks not only to advance technological development but also to minimize environmental and biological impacts. The primary objective of Green Tribology is to integrate tribological advancements with broader sustainability goals (including the reduction of carbon emissions), conservation of resources and energy, and the efficient utilization of materials.

Achieving a balance between the benefits of technological progress and its environmental and biological consequences can be challenging; however, it is of paramount importance. The future of both society and the planet may depend on the successful incorporation of Green Tribology principles into technological design and engineering practices.

Research in this area should focus on the relationship between energy consumption and human development, the fundamental principles and application domains of Green Tribology and the ways in which these principles can be employed to develop sustainable solutions for emerging technological challenges. Such efforts are essential for promoting environmentally responsible innovation and ensuring long-term technological sustainability.

An important aspect of increasing energy consumption is the growing production of consumer goods, the expansion of utility services, and the increasing operation of various types of equipment. To date, this issue has not received sufficient attention from either policymakers or the general public. According to data from the Organisation for Economic Co-operation and Development (OECD) (Bibas et al., 2019), global raw material extraction is projected to increase from 92.1 billion tons in 2017 to 167 billion tons by 2060 (Tzanakis et al., 2012; United Nations Environment (n.d.)); it is evident that virtually all material consumption results in carbon dioxide and greenhouse gas emissions.

Growing awareness of the adverse environmental impacts associated with chlorofluorocarbons (CFCs) used as refrigerants, chlorinated hydrocarbons employed in industrial lubricants, and lead-and sulfur-containing fuel additives has led to restrictions and bans on the use of these hazardous substances. Consequently, researchers have been required to develop alternative materials while maintaining the low-friction characteristics, functionality, and reliability previously provided by banned materials. Designers are therefore challenged not only to reduce frictional losses but also to develop environmentally benign lubrication technologies that can replace conventional lubrication methods through the use of eco-friendly lubricants. Addressing these challenges requires a comprehensive tribological approach.

Factors such as wear and friction losses, durability, and condition monitoring of the principal components of mechanical systems must be carefully considered. These tasks require a profound understanding of engineering principles and a sound scientific basis for their implementation. It is at this point that tribology assumes a central role (Jost, 1966). Tribological analysis has the potential to generate substantial environmental and economic benefits. By reducing friction, extending the service life of mechanical systems and minimizing wear, tribological improvements can contribute significantly to the reduction of global carbon emissions (Woydt et al., 2019).

The importance of tribology as a discipline with direct relevance to national economies was demonstrated as early as 1977 by the American Society of Mechanical Engineers, which estimated potential energy savings of approximately 40%, equivalent to about 10.9% of gross domestic product (GDP); similarly, in 1976, the German Federal Ministry responsible for Research and Development reported potential savings exceeding 2.0% of GDP. Subsequent detailed analyses of a comprehensive two-year study conducted in 2006 by the Chinese Tribology Institute, covering six industrial sectors, confirmed estimated annual savings of approximately USD 41.4 billion (Zhang & Xie, 2009), corresponding to about 1.55% of China's GDP (Table 1).

Table 1: Potential Energy Savings Identified Through Tribological Analysis (Xu, 2013).

Study	Year of Publication	Energy-Saving Potential		Potential Savings Due to Reduced Friction and Wear	
		Energy Demand (%)	Primary Energy Demand in 2017 (EJ)	GDP (%)	Estimated Economic Savings in 2017 (€ Billion)
Jost (U.K.)	1966	5%	0.4	2% of GDP in the United Kingdom	€46.5 billion
ASME (USA)	1977	10.9%	10 (93 EJ)	-	-
BMFT (Germany)	1976	-	-	1% of GDP in Germany	€32.7 billion*
China (Industry Only)	2006	-	-	1.55% of GDP	US$ 41.4 billion

Note. *1 EJ = 10^{18} Joules; ASME = American Society of Mechanical Engineers; BMFT = Bundesministerium für Forschung und Technologie (Federal Ministry for Research and Technology), currently known as the Federal Ministry of Education and Research (BMBF). Economic losses expressed in absolute monetary terms.*

In the future, the primary drivers of technological progress in tribology will be based on the principles of sustainable ("green") tribology and zero-carbon emissions (Toyoda, 2007). In a broader sense, these may be defined as the scientific and technological aspects of tribology that contribute to achieving ecological balance while minimizing environmental and biological impacts. These objectives include:

- Increasing the durability and service life of products in order to reduce material consumption, which is invariably associated with carbon emissions;
- Reducing friction to achieve energy savings and lower carbon emissions.

In 2015, the United Nations General Assembly adopted the 17 Sustainable Development Goals (SDGs) as globally recognized guidelines for achieving environmentally sustainable development (United Nation General Assembly, 2015).

These goals are indispensable for the efficient use of energy resources and environmental protection. At the same time, they contribute to reducing energy losses and addressing economic challenges, since more efficient utilization of equipment can result in substantial capital savings.

Recent analyses in the field of fundamental tribological research have highlighted several environmental concerns associated with advanced technologies for the production of sustainable tribological materials, including biodegradability and environmental toxicity. Examples include ceramic bearings for spacecraft pumps and chemical surface modification techniques employed in tribological systems. The application of tribological principles to address energy losses caused by friction demonstrates the significant potential of tribology in solving environmental challenges (Janahmadov, 2023; Canəhmədov, 2025; Janahmadov et al., 2023).

Tribological advancements play a crucial role in reducing friction losses within automotive internal combustion engines. In 2018, approximately 1.3 billion vehicles were in operation worldwide, while annual global vehicle production reached 95–100 million units. It has been estimated that a 10% reduction in mechanical losses due to friction within the powertrain could result in approximately a 1.5% reduction in fuel consumption. Over the service life of a vehicle, this corresponds to savings of approximately 340 liters of gasoline. Considering the vast number of vehicles currently in operation, even this seemingly modest saving - estimated at approximately USD 350 per vehicle - could generate substantial economic and environmental benefits (Janahmadov, 2023).

To address these challenges, extensive investigations have been conducted, and a new roadmap (framework) for the application and development of artificial intelligence and machine learning in tribology has been proposed. This framework aims to establish a systematic approach, generate novel research ideas, and enhance the efficiency of solving tribological problems (see Figure).

Furthermore, the availability of increasingly comprehensive and accurate tribological data is expected to improve the reliability and durability of mechanical components. It has been established that laboratory testing of material combinations under conditions closely resembling real operating environments remains the most accurate method for obtaining fundamental tribological data for reliability assessment purposes.

The effective integration of tribological knowledge with electronics and mechanical engineering will enable developers of tribological technologies to expand the boundaries of renewable and environmentally friendly energy systems, such as wind and tidal turbines. Realizing the full potential of tribology in the twenty-first century will require the efficient and sustainable utilization of natural resources (see illustrative example in the Figure).

Statistical evidence further demonstrates that the influence of tribology on the ecosystem and its future development are closely linked to the interaction between human intelligence, energy systems, and artificial intelligence.

Conclusions

The present review has developed a generalized framework describing the application and development of artificial intelligence in tribology. Based on this framework, a systematic approach has been formulated, highlighting the interactions between the fundamental characteristics of tribology and various scientific disciplines.

The analysis demonstrates not only the complexity of tribology as a mechanical system science but also the inherently interdisciplinary nature of the efforts required to study and advance the field.

The findings indicate that future progress in tribology will increasingly depend on the advancement of artificial intelligence concepts, machine learning methodologies, triboinformatics, and Green Tribology. In this regard, it is considered essential to direct the attention of future tribologists toward the development of scientific disciplines such as mechanical engineering, physics, and materials science within the framework of next-generation information and communication technologies.

Because Artificial Intelligence (AI) possesses advanced machine learning (ML) capabilities and triboinformatics provides powerful high-speed data-processing tools, these technologies can assist researchers in rapidly identifying valuable patterns, trends, and relationships within complex and heterogeneous datasets.

Recent advances achieved through the application of Artificial Intelligence (AI), particularly Artificial Neural Networks (ANNs), in tribological research are highlighted. The presentation and discussion of successful studies conducted using these approaches in a tribological context demonstrate that such methods are capable of accurately and efficiently predicting tribological characteristics, including friction, wear, lubrication behavior, and surface modification processes.

Future technological progress in tribology is expected to be driven primarily by the principles of sustainable Green Tribology and zero-carbon-emission technologies, thereby contributing to the achievement of biological and ecological balance.

As a result of extensive research, a scientifically grounded roadmap (framework) for the application and further development of Artificial Intelligence and Machine Learning in tribology has been proposed. By establishing a systematic understanding of the field, this framework is expected to enhance the efficiency of solving complex tribological problems and to stimulate the development of new research directions.

Conflict of Interest

The authors declare that there are no conflicts of interest requiring disclosure in relation to this study.

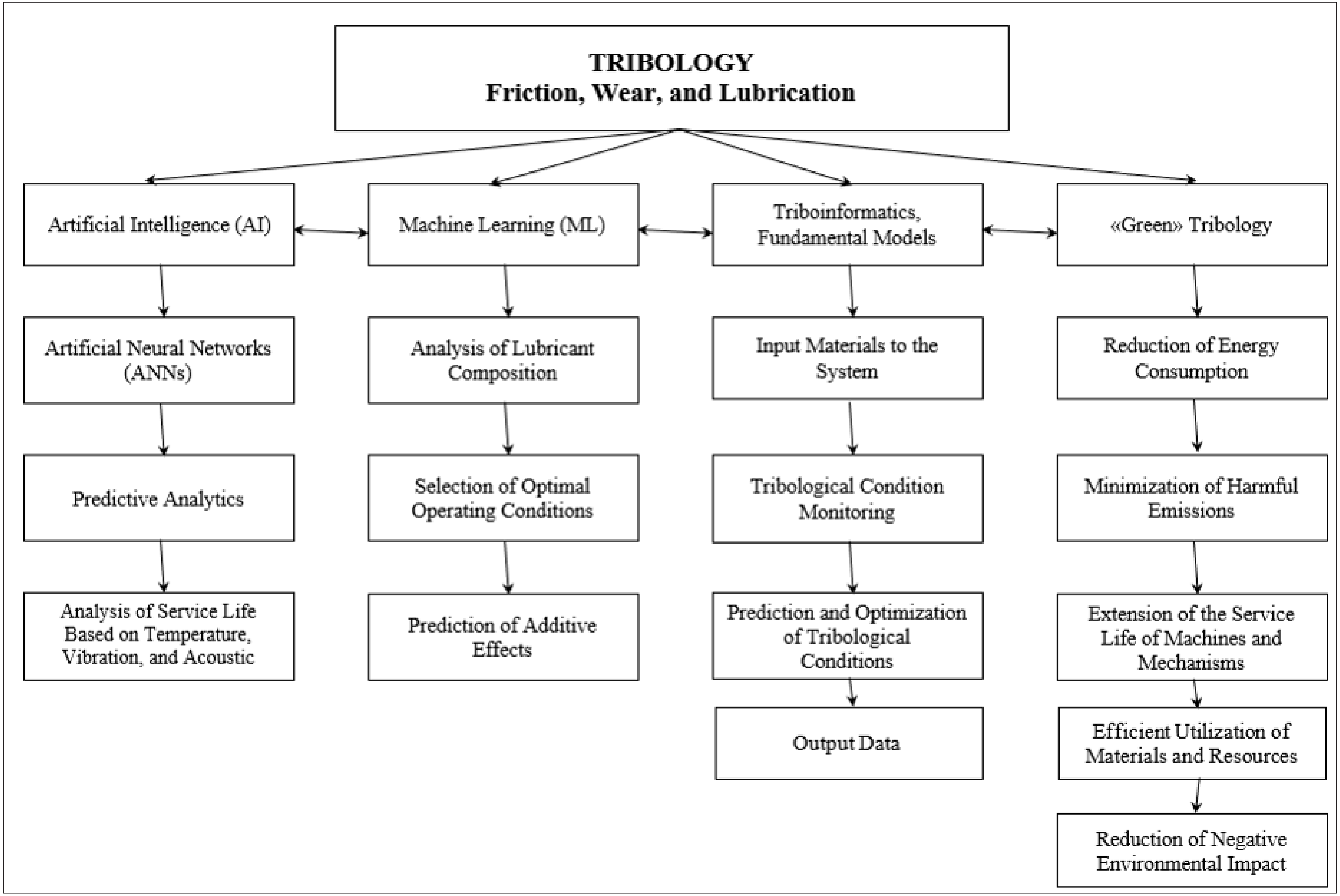

Figure 1: Application of Artificial Intelligence in Tribology and its Development Scheme

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