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History of tribology: Assessing the prehistoric impacts, progress on industrial and scientific revolution eras, and contemporary interdisciplinary research trends

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ABSTRACT

The present review focuses on the progress of tribology from the prehistoric period to the contemporary interdisciplinary research trends. During the Paleolithic period, humans used sliding friction, generated inadvertently, to make fire. The Paleolithic inhabitants possessed the knowledge to wear the chloritolite blank to fabricate a bracelet using sophisticated material removal processes. Furthermore, they wore the tooth by making holes, filled them with fillings, intended as a pathologically motivated intervention. Humans wore the tooth by in vivo drilling in the Neolithic period, used as a remedial or soothing dental procedure. The Egyptians poured water on sand to ease the movement of the statue mounted on a sled, and recently, compared to the sled dragging on dry sand, the capillary water bridges easing the sled dragging on wet sand is experimentally observed. Bearings are proposed in the renaissance era, and Leonardo da Vinci initiated friction studies, which witnessed significant progress in the industrial revolution era. The industrial revolution ushered in the use of solid lubricants and lubricating oils and grease with additives. Studies in the scientific era discussed friction, wear, and lubrication problems and reported novel, proven solutions. The expansion of tribology research into different disciplines gave birth to novel interdisciplinary studies: the mimicking of biological structures to improve adhesion, use-wear patterns of ground stone tool surfaces, tribological behavior of artificial implants and medical devices, friction in oral processing, and lubricity of two-dimensional lamellar material. Green tribology is the recent focus and it promotes sustainable tribology research for the sustenance of the earth.

Keywords: History of tribology, Interdisciplinary tribology research, Green tribology, Prehistoric tribology, History of lubrication

1. Introduction

Tribology focuses on friction, wear, and lubrication of interacting surfaces in relative motion [1, 2]. The word “tribology” was first introduced in a historical report prepared by a Working Group chaired by Peter Jost in 1966. The study reported the yearly monetary losses incurred due to friction and wear and recommended that industries adopt efficient tribology practices [3]. The history of tribology gained significant interest among scientists and historians, who aim to understand the historical influence and scientific impact of friction, wear, and lubrication. During ancient times, friction-reducing measures aimed to ease the habitual functions [4, 5], and the ancients obtained benefits by utilizing the wear process [6]. Several proposals were made in the renaissance era on friction and lubrication [7, 8], and the industrial revolution marked significant studies that dealt with friction and wear [3]. These studies recognized the problems about friction and wear and suggested standardized practices to deal with the same [3, 9]. Over time, significant progress has been made in tribology due to the innovations in microscopy, development of novel tribometers and lubricants, simulation capabilities of friction and wear, synthesis of lamellar solids and nano-coatings, and formation of textures, to name a few [1, 3, 8, 9]. Against this backdrop, studies on the history of the progress of tribology research were first reported in the mid-twentieth century. Some of

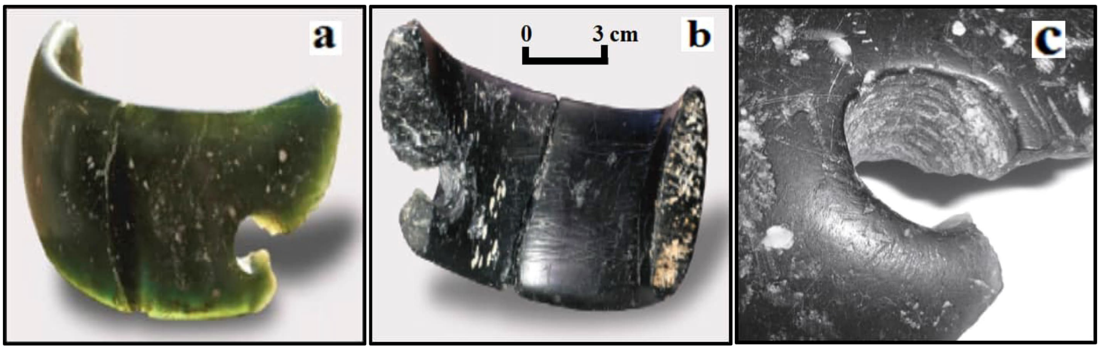

Figure 1. The Paleolithic bracelet: (a) external surface, (b) internal surface, and (c) drilling of the lateral opening. Reprinted from [16], Copyright(2021), with permission from Elsevier.

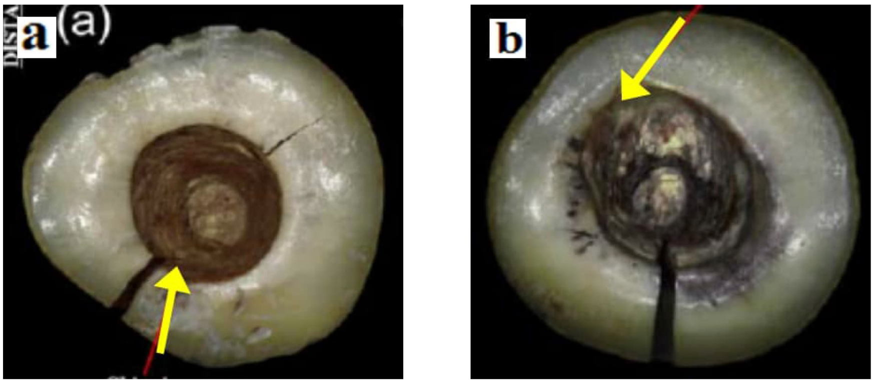

Figure 2. The Late Upper Paleolithic dentistry: (a) upper first right incisor surface with filling (marked with arrow) and (b) upper first left incisor surface with filling (marked with arrow). Reprinted from [17], Copyright (2021), with permission from Wiley.

the notable reports include the review of the history of lubrication [10], the monograph that emphasized the history of multi-disciplinary approaches (mathematical, physical, and mechanical) toward friction [11, 12], and the reports that discussed the practices used in early history to prevent wear [13]. Several studies reported in the 1990s also discussed the history of tribology [14].

The reports that deal with friction during prehistoric periods [6], friction-reducing measures [5] and lubrication practices [11] of different civilizations during specific periods, modern innovations on tribology [1], and sustainable tribology research [15] have frequently been reported. These reports discuss specific topics on innovations or practices related to friction, wear, and lubrication. Moreover, their scope of discussion is limited to specific periods in history. However, the growth of tribology as an interdisciplinary science that addresses the standard (friction due to sliding action [1]) and sophisticated (friction at molecular scale [9]) tribological problems is phenomenal; this necessitates an in-depth review focusing on the history of research progress on friction, wear, and lubrication. In the present study, the history of tribology from the prehistoric period to recent interdisciplinary research trends is reviewed, emphasizing significant landmarks concerning tribology.

2. History of tribology research

The history of the progress of tribology research is discussed in the following sections.

2.1. Paleolithic period: Lower, Middle, and Upper Paleolithic

Paleolithic people used the temperature rise in sliding contact to create sparks [2]. The sliding contacts used were sticks, stones, or some other available materials. The Paleolithic people rotated the round end of a wood stick against a counter wood section at high sliding speed; this generated frictional heat. The heat generated on the hot surfaces (wood stick and wood section) leads to the fire of the small fragments of wood and dried leaves placed around the rotating contact [2].

The Paleolithic people fabricated aesthetic ornament (bracelet) from chloritolite blank during the early Upper Paleolithic period (circa (c.) 30,000 years ago) [16]. The bracelet (figure 1(a), (b), and (c)) was found from the Denisova Cave, Altai mountains of Siberia, Russia. The machining techniques applied for producing the bracelet were (a) grinding on various abrasives, (b) polishing with skin, (c) carving by a chisel, (d) boring with the aid of a small mobile tool, and (e) high-speed drilling and rasping [16]. The Paleolithic craftsmen possessed the knowledge to derive advantage from different material removal processes (wearing the chloritolite blank) for aesthetic purposes (fabricating a bracelet). The sophisticated technology used to produce the bracelet shows the exemplary manual skills and advanced practices of the

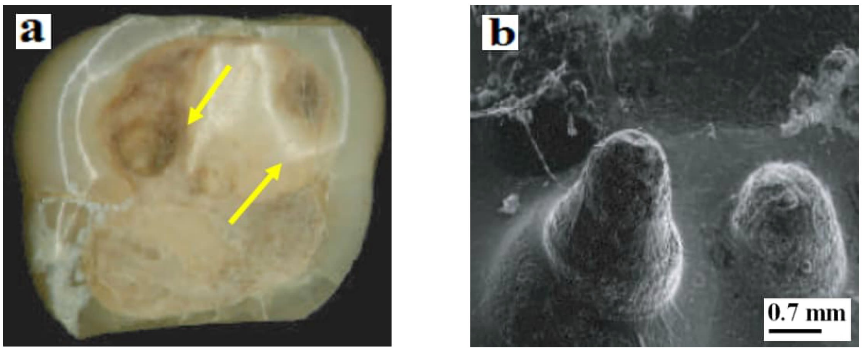

Figure 3. (a) in vivo perforations (marked with arrow) on the occlusal surface and (b) negative replicas of the perforations. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Nature [18] (2021).

Upper Paleolithic cave inhabitants.

The excavation at Riparo Fredian, Italy, indicated the evidence of Late Upper Paleolithic dentistry. Both the upper first incisors of the human (namely, Fredian five, dated 13,000 to 12,740 years ago) have large holes on their surfaces, extending into the pulp chambers [17]. The in vivo dentine wear to make the holes suggest tool use. The process of wear is advantageously utilized to remove the infected pulp, and then, the holes are filled with a composite filling (marked with arrow in figure 2(a) and (b)), completing the pathologically motivated intervention.

2.2. 7000-5500 before common era (BCE): The Neolithic period

The excavation at the Neolithic site of Mehrgarh in Baluchistan revealed that humans of the Neolithic period (c. 7500 to 9000 years ago) used teeth drilling as a dental procedure for therapeutic or palliative purposes [18].

Neolithic humans wore the tooth by drilling, which is indicative of their knowledge of deriving advantage (improved oral health) from the process of material removal (wearing the tooth material). Two in vivo perforations (marked with arrow in figure 3(a)) are made on the occlusal surface by a drilling tool equipped with a flint head. The larger perforation has the maximum diameter (MD) and depth of 1.6 mm and 1.5 mm, respectively, and the other is of 1.3 mm MD and 0.7 mm depth [18]. The negative replicas (figure 3(b)) of the perforations revealed their slight inclination.

2.3. 3500 BCE: The Late Neolithic period

In the Late Neolithic period, a significant invention from the tribological viewpoint has been the wheel [3]. The transition from sleds to wheeled vehicles was seen during this period. Wheels significantly reduced friction and eased transportation compared to sleds [4]. An expertly made prehistoric wooden wheel (figure 4) with axle was found in pile-dwellings on Ljubljansko barje, Slovenia [19]. It is one of the oldest wooden wheels (5,150 years old, approx. [19]). Nevertheless, it is to be noted that the humans of the Late Neolithic period did not comprehend the physical concepts of force, friction, and momentum [4].

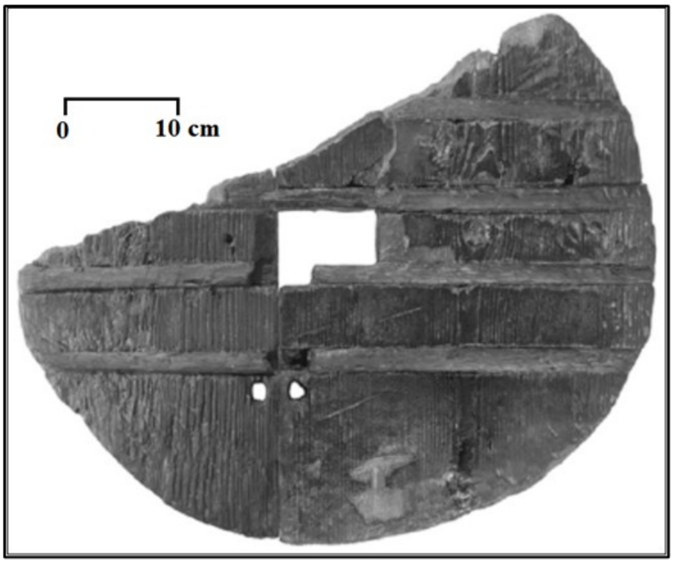

Figure 4. A prehistoric wooden wheel with axle hole made by pile-dwellers of Ljubljansko barje, Slovenia [19]. Reproduced by permission from the Respiratory of University of Ljubljansko, Slovenia.

2.4. 1800 BCE: Role of the ancient civilization of Egypt in lubrication

The role of ancient Egyptian civilization in lubrication is discussed in the following sections.

2.4.1. Lubrication using gypsum

Gypsum formed a thin layer of viscous mortar to slide massive stone blocks. The viscous mortar could function as a lubricant to reduce friction, enabling accurate positioning of the blocks at the intended location [14].

2.4.2. Lubrication by pouring liquid in front of the sled

Tomb paintings in El-Bersheh (c. 1880 before common era (BCE)) and Saqqara (c. 2400 BCE) indicate lubrication with water to aid the transportation of giant statues [14]. Men pouring liquid from jars are shown in the paintings [10, 14]. Dowson [14] stated that the liquid poured from the jar is water, and the statue-mounted sled is lubricated with water as it is dragged over the wet sand. The man pouring water from the jar in the Saqqara painting (region of wet sand is marked with dotted rectangle in figure 5(a)) has

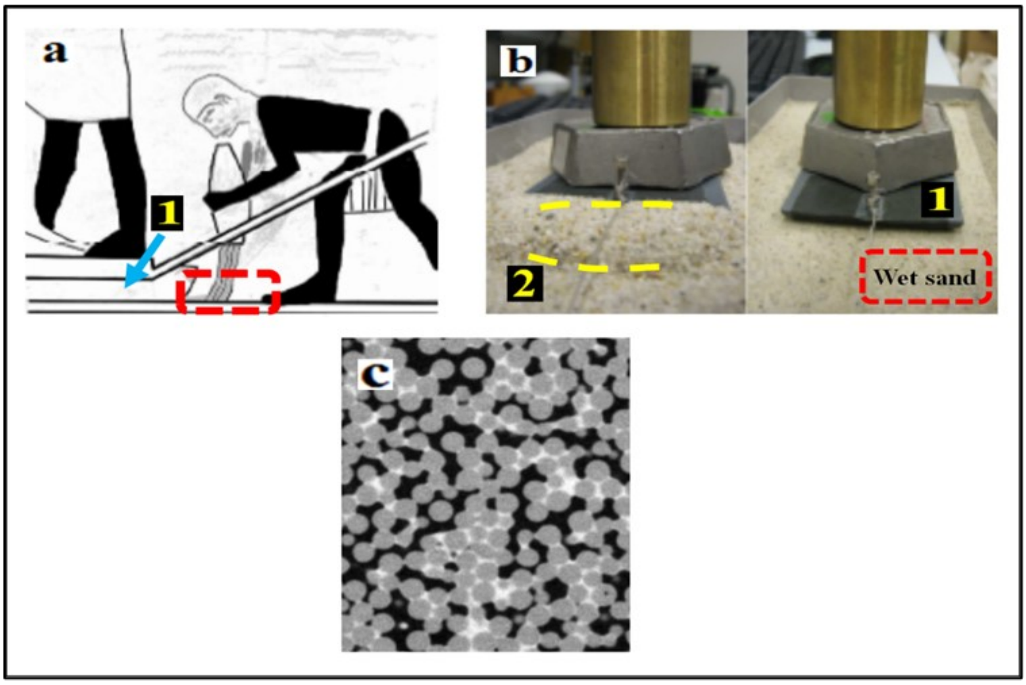

Figure 5. (a) man pouring liquid from a jar in Saqqara painting (1. sled and region of wet sand is marked with dotted rectangle) [11] (CC BY-NC-ND 4.0), (b) experimental setup showing sled dragging (heap formation of dry sand is marked with dotted line and wet sand is marked with dotted rectangle) (1. sled and 2. dry sand), and (c) X-ray microtomography showing capillary regime. (figure 5(b) and (c) is reprinted from [21], with the permission of APS publications).

been widely credited as the first tribologist in the recorded history.

2.4.3. Lubrication of the chariot axle using animal fat

A chariot of ancient Egypt was found, probably from 1400 BCE, with trace elements at its axle [10]. In the 1920s, a small sample (weight-0.038 g) of this element was analyzed. The sticky and greasy sample had the following constituents: (a) road dirt such as quartz sand and (b) a compound of aluminum, iron, and lime [14]. It had a melting point of 49.5 °C, and the Cairo museum indicated the sample to be mutton or beef fat [10, 14].

2.4.4. Role of Egyptian civilization in lubrication: critical views and experimental confirmation

Nosonovsky [11] reported differing views to the broadly acknowledged findings on the role of Egyptian civilization in lubrication. According to Nosonovsky [11], using gypsum for the accurate positioning of stone blocks is not, as such, a lubrication process but a technique to fit the large stones together. The men pouring water from the jars might have been priests who performed the ritualistic act (pouring water from the jar), probably to purify the statue (body) of the Pharaoh [11]. Newberry [20], an Egyptologist, observed that water pouring in front of the sled is purely a ceremonial act; even in large quantities, water may not aid the sled dragging.

To this end, a recent study substantiated the ease of sled dragging over the wet sand (marked with dotted rectangle in figure 5(b)) [21]. Water added to the sand forms capillary water bridges between the sand grains; thus, the shear modulus of the sand increases that promotes the sliding. A three-dimensional (3D) X-ray microtomography (figure 5(c)) shows the liquid pockets (white), suggestive of the capillary regime formed on the sand. In dry sand, a heap was formed (marked with dotted line), which tends to impede the sled movement, as it was made to slide on the sand. As a result, the friction coefficient obtained is higher than when the sled moved on sand wetted with 5 % water. Based on these experimental observations, Fall et al. [21] stated that the Egyptians could have dragged the sled over the wet sand with the available workforce.

2.5. 500 BCE: Role of ancient Chinese civilization

Around 500 BCE, the Chinese chariots were equipped with cast iron axle bearings [5]. Three types of cast iron

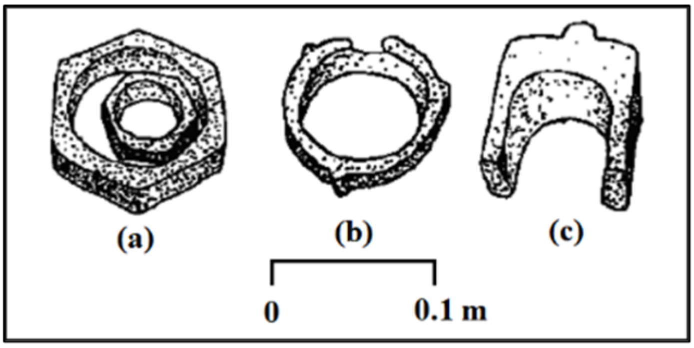

Figure 6. Types of cast iron axle bearings of Chinese chariots: (a) hexagonal, (b) circular, and (c) half-metal [5]. CC BY -NC-ND 4.0.

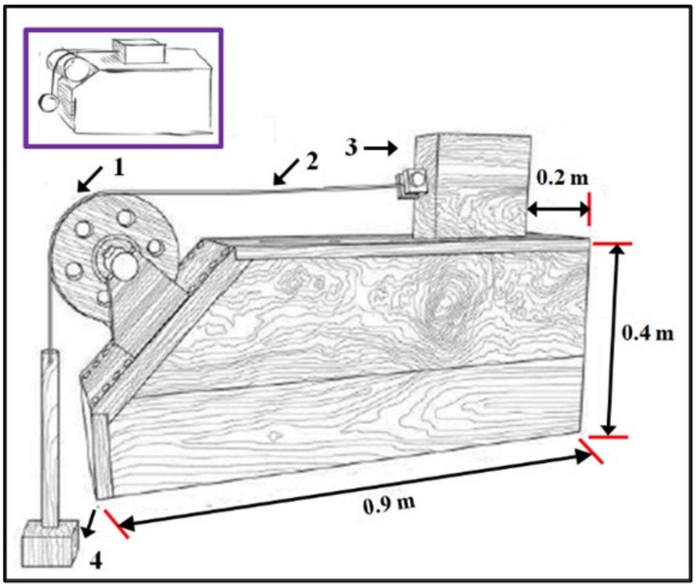

Figure 7. Schematic of the apparatus fabricated according to the illustration (upper left inset) in the Codex Arundel of da Vinci (1. wooden pulley assembly, 2. thin rope, 3. sliding block, and 4. Deadweight). Adapted by permission from Springer Nature Customer Service Centre GmbH: Nature [23] (2014).

axle bearings were used in chariots: (a) hexagonal (figure 6 (a)), (b) circular (figure 6(b)), and (c) half-metal (figure 6(c)) [5].

2.6. 1450-1600 CE: Scientific developments of tribology during the renaissance era

The renaissance era witnessed significant scientific developments concerning tribology. The first quantitative studies on friction have been broadly attributed to Leonardo da Vinci [22]. He made three noteworthy observations that antedated the development of laws of friction: (a) friction does not depend on apparent contact area, (b) the frictional resistance is directly proportional to the applied load [23], and (c) friction is consistent, and its value is 0.25 [23]. Pitenis et al. [23] fabricated da Vinci's friction measuring apparatus (figure 7) to understand the experimental conditions that produced the findings above. The apparatus was made using the illustration (upper left inset of figure 7) from da Vinci's manuscript called Codex Arundel (date between CE 1478 and 1518).

The experiments revealed that the rough cut and the brusquely squared specimen of dry wood exhibit a friction coefficient of 0.25. The rough preparation of the specimen and the contamination of its surfaces due to extensive handling might have contributed to the consistent and low value of friction coefficient. The following are some of the critical proposals of Leonardo da Vinci to reduce friction: (a) a bearing alloy (30 % copper and 70 % tin), (b) rolling friction bearings that relied on rolling friction, (c) sleeve bearings mounted on rotating rollers, (d) ball bearings with separators (cages), (e) partial bearings to facilitate oscillatory movements, (f) using leather or oil-soaked leather in-between the sliding surfaces of pump rods, and (g) using tiny grains (powder) for lubrication between the contact surfaces [8]. During the sixteenth century, the engineers designed various bearings: plain bearings for a rag-and-chain pump and plain bearings and rollers for manually operated worm gear mechanisms [7].

2.7. 1600-1750 CE: The pre-industrial era

In 1699, Guillaume Amontons defined the two classical laws of friction [9]: '(a) The force of friction is directly proportional to the applied load, and (b) The force of friction is independent of the apparent area of contact.' Then, in an era where studies on lubrication are in their infancy stages, Isaac Newton presented the law of viscous flow, defining the internal friction of fluids [3].

2.8. 1750-1850 CE: The industrial revolution era

During the seventeenth century, the rapid population growth caused a high demand for products in different industrial sectors. In this context, several studies examined friction and wear to enhance the functioning of industrial machinery [7]. Leonhard Euler clarified the distinctions between static and kinetic friction; the Greek symbol μ to denote the friction coefficient is attributed to Euler [9, 24]. Charles Coulomb formulated friction formulas based on his experimental observations [25]. Coulomb added the third rule to the classical laws of friction [1]. This third law states that the friction coefficient is independent of the sliding speed once the motion has commenced. He studied the sliding friction of plane and rough surfaces [3], stiffness of ropes, the friction of rotating elements, rolling friction using an apparatus, and normal load applied to the contact surfaces [9, 25]. In 1785, Samuel Vince [26] attributed static friction to the cohesion and adhesion phenomenon. Sir John Leslie [27] studied the friction of solids extensively and observed that the tendency of asperities to deform with time influences friction rather than adhesion.

Different vegetable and animal oils were used to lubricate machinery during this period, including olive oil, rapeseed oil, coconut oil, palm oil, sperm oil, lard oil (melted pig fat) [3], neatsfoot oil, groundnut oil, castor oil [8], and whale oil [28]. Greases and semi-fluid lubricants were prepared by mixing the melted beef or mutton fat with graphite (Gr) [8]. The development of mineral oil in 1812 led to the formulation of different mineral-oil-based lubricants, and the first Gr-containing lubricant was patented in 1835 in the United Kingdom [3]. A grease formulation patented in 1835 consisted of washing soda, pure fat, and palm oil [8]. Whale or lard oil combined with coal tar and asphalt was, patented in 1847, proposed as a lubricant [28]. Gr and talc were administered in small amounts whenever the bearings exhibited distress signs. Isaac Babbitt developed a low-friction metal, an alloy of tin, antimony, and copper [7].

2.9. 1850-present: The scientific era

Studies on friction, wear, and lubrication are extensively reported in this era. In 1875, studies of rolling friction by Osborne Reynolds experimentally established that there are always regions in no-slip contact and regions that undergo slipping when two bodies are in contact [29]. In 1881, Heinrich Hertz analyzed the contact between two elastic bodies with curved surfaces [30, 31]. In 1883, Nikolai Petrov conducted studies on viscous friction and proposed Petrov's law to evaluate the power loss of bearings [32]. In 1886, Osborne Reynolds [33] formulated the hydrodynamic theory of lubrication [8] and applied the theory to Beauchamp Tower's experiments. In 1898, Richard Stribeck developed the Stribeck curve used in bearings design and explained different lubrication regimes [31].

In 1904, Arnold Sommerfeld [34] solved the Reynolds equation and presented the hydrodynamic lubrication theory with the analytical solution used in the design of the bearings. In 1914, Ludwig Gumbel synopsized the Stribeck results in the single curve using dimensionless parameters [35]. In 1917, Langmuir and Blodgett invented Langmuir-Blodgett thin films, which significantly reduced wear and friction, and the thin films are used as model systems to study boundary lubrication [36]. In 1929, Tomlinson [37] discussed friction from molecular interaction and energy dissipated from the moving bodies. In 1953, Archard [38] stated that the wear rate is proportional to the applied load. The plastically deformed material is removed in the form of lumps at the contact areas.

The period from the 1940s to the 60s marked the emergence of the theory of elastohydrodynamic lubrication (EHL), which discussed the hydrodynamic lubrication characteristics of gears and rolling bearings [39]. In 1949, Grubin solved the EHL line contact problem by combining the elastic deformation behavior of the solid contact bodies and the hydrodynamic flow of the lubricant, which included the lubricant's pressure-viscosity relationship [40, 41]. In one of the earlier studies, conducted in the 1950s, Ocvirk and Du Bois [42] investigated the impact of the end leakage of the oil from the fluid film of the short plain bearings and approximated a solution. In addition, they experimentally analyzed the lubrication and friction characteristics of the short journal bearings and long journal bearings [43]. In 1976, Hamrock and Dowson [44] performed a numerical study of isothermal EHL characteristics of the point contact. Furthermore, they studied the influence of the ellipticity parameter on the obtained solutions of the point contact problem [45]. During this period, optical interferometry was brought into use to gather the oil film's thickness; experimental investigations were extended to mixed and boundary lubrication studies, where asperity contacts, lubrication with the aid of thin films, and non-steady-state operating conditions were considered vital experimental parameters.

In the 1950s, Bowden and Tabor [46] proposed the friction theory that detailed friction in terms of two friction components, namely, (a) adhesive component and (b) plowing component. In 1966, Greenwood and Williamson [47] proposed that the contact deformation of the two nominally flat surfaces depends on the surfaces' topography, and they coined the term 'elastic contact hardness', a quantity that depends on the elastic characteristics and topography of the contact surfaces. In the 1960s and 70s, Donald Buckley [48, 49] studied the role of adhesion and surface chemistry on friction, wear, and lubrication. The influence of crystal orientation of solid lubricant particles in lubrication is also discussed [9]. In the 1960s and 70s, Kragelsky made significant advancements in the calculation of wear and friction. In addition, the external factors that influence the friction and lubrication of contact surfaces were also discussed [9, 50]. In 1973, Nam Suh [51] proposed a theory for the wear of metallic materials. The theory is based on surface dislocation, subsurface cracks and voids formation, and merging of cracks due to shear deformation of the surface. In the 1970s and 80s, Pradeep Rohatgi and coworkers [52] extensively studied the fabrication and tribological characteristics of self-lubricating Gr-reinforced composites. Polymer, metal, and ceramic matrices use a broad range of carbon-based materials as reinforcement elements to improve their anti-friction and anti-wear characteristics [53]. These materials include carbon nanotubes (CNTs), single-walled CNTs, multi-walled CNTs, graphite, fullerenes, single-layer, few-layered, and multi-layered graphene, and nanodiamonds.

In 1987, Kaneko et al. [54] fabricated a scanning tunneling microscope, one of the earliest attempts to fabricate one, to study wear at the nanoscale, where the physical and chemical properties of the contact surfaces of the read/write head and the medium of recording are of paramount importance. In the 1990s, Bhushan [55] began investigating the tribological behavior of head-disk (tribo-couple) interfaces of magnetic storage devices. During this period, the influence of wear, friction, lubrication, adhesion, and temperature at the head-disk interface was significantly explored and reported.

Tribology-centric research has gained significance over the past couple of decades in the pavement industry. Warm-mix asphalt technology, a novel technology for fabricating materials for the pavement laying sector, reduced production temperatures by about 20 to 50 ºC [56]. In this technology, the mixing and densification of the asphalt mixes takes place at lower temperatures; this phenomenon is due to the aggregate particles that are in relative motion at the contact zone, offering low friction. The friction coefficient quantifies the lubricating characteristics of the asphalt binder between particle aggregates.

From a biotribology perspective, the topic of amputation and prosthetic limb fitting gained significance in the early 1940s [57], prompting surgeons to acknowledge the sophisticated nature of friction that arises during the interaction between the floor and prosthetic limb. During this period, researchers designed several knee models (Osterly Gestange knee and Stabilax knee) and thigh sockets [58]. The data collected from prosthetic users motivated the research, with significant consideration given to friction-related aspects.

In the past couple of decades, researchers have conducted some intriguing tribological studies by

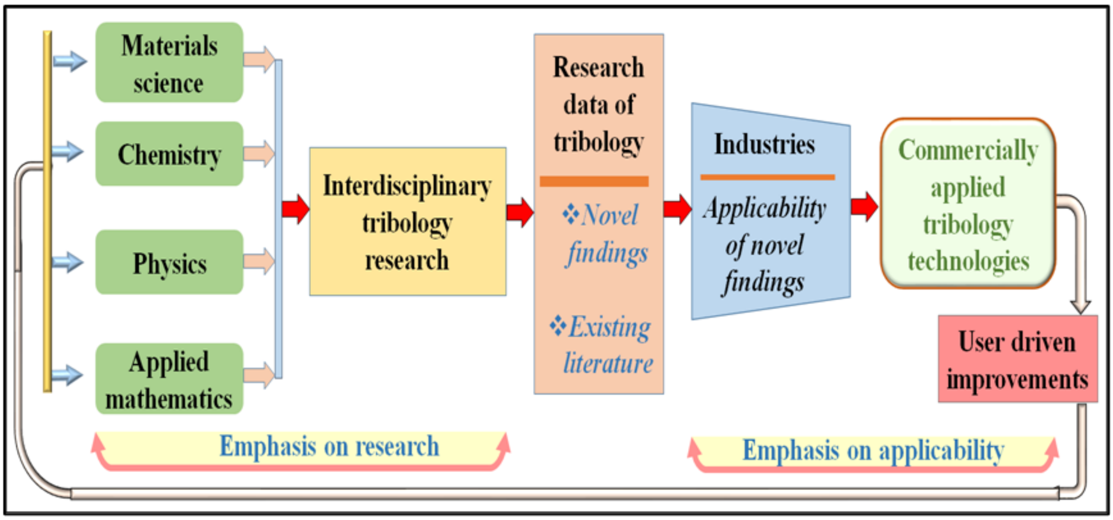

Figure 8. Schematic showing the closed-loop cycle of interdisciplinary tribology research.

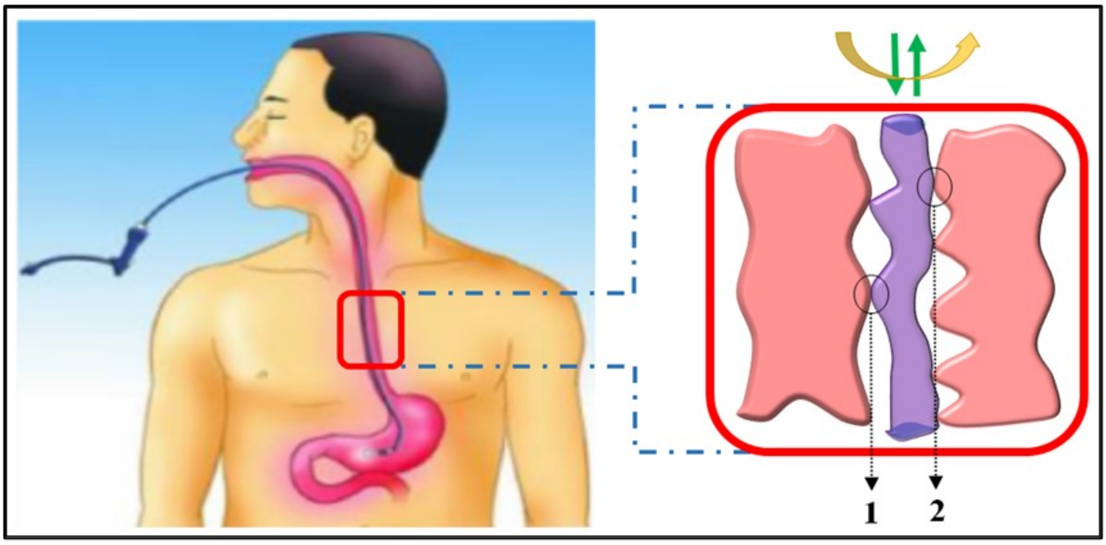

Figure 9. Schematic showing endoscopy insertion through the upper gastrointestinal tract (1 and 2 are friction-induced regions) (green and yellow arrows, respectively, mark the linear and rotation motions of the endoscopic wire). Adapted from [66]. CC BY-NC-ND 4.0.

mimicking the characteristics of nature to obtain beneficial tribological properties. Biomimetic tribology beneficially combines tribology with the natural sciences, intending to harness the features of biological systems to improve the characteristics of tribological systems [59]. The aim is to understand the mechanisms that influence the anti-friction or friction, wear or wear-resistive behavior, adhesion or anti-adhesion characteristics, and lubrication characteristics observed in biological systems. In the last decade, tribology research predominantly became interdisciplinary [60]. The following section deals with the interdisciplinary advances in tribology.

2.9.1. Interdisciplinary advances in tribology

Interactions of tribo-couple elements are highly sophisticated, and their understanding requires interdisciplinary research expertise involving applied mathematics, physics, chemistry, and materials science [61]. Schematic (figure 8) shows the closed-loop cycle of interdisciplinary tribology research. It is to be noted that the industries assess the commercial applicability of the research outcome, which may be tribologically critical components, tribogenerators, or lubricants. When commercially implemented, the market feedbacks are sought to improve the quality of the research outcome, and the valid user-driven improvements are incorporated into the interdisciplinary tribology research approach.

The interdisciplinary research on tribology includes studies on bioinspired contact textures (biomimetic tribology) [62], ground-stone tool surfaces (archaeotribology) [11, 63], wear of novel artificial implant materials (biotribology) [64, 65], tribology of medical devices [66], the Physico-chemical mechanisms concerned with sensory perceptions and oral processing (soft solid tribology or food tribology) [67], and lubricity of novel two -dimensional (2D) nano additives (nanotribology) [68, 69].

Some studies in the aforementioned interdisciplinary tribology are elaborated in this section.

The emergence of soft solid tribology or food tribology concerns the friction properties of food processing in the oral cavity. In 2019, Rudge et al. [67] summarized the studies that discussed the relevance of friction properties in sensory perception and oral processing. In this food tribology, soft, hydrated, and heterogenous food is assessed for its frictional properties. The oral cavity forms an essential aspect of tribo-testing, and food scientists commonly use elastomers and hydrogels to mimic the mostly wet and soft nature of the oral cavity. Lately, friction-induced during the insertion of medical devices into the human body has gathered significant attention. In the case of gastrointestinal complications of humans, passing a gastrointestinal endoscope, via the digestive tract, to the location of the lesion forms the primary clinical intervention step. The repeated insertion (marked with green arrow), retention (marked with green arrow), and rotation operations (marked with yellow arrow) of the endoscope in the digestive tract may cause friction-induced damages (figure 9) inside the tract [66]. Accoto et al. [70] observed the difficulty of the minimally invasive devices to pass through the complexly structured digestive tract. The variation of friction coefficient is measured by sliding constant weight blocks on the digestive tract surface under controlled conditions. The sliding speed of the blocks are varied, and the friction coefficient increased proportionally with the sliding speed. In a different study, which is also concerned with human well-being, novel biocompatible materials are synthesized for artificial implants. Cui et al. [65] synthesized Polyvinyl alcohol (PVA) hydrogel and deposited the same on the surface textured titanium alloys. The hydrophilic surface of the material has 32° static water contact, and the friction coefficient (as low as 0.01) is similar to that of the natural cartilage. Furthermore, the addition of graphene oxide into PVA hydrogel enhanced its mechanical and tribological properties, emerging as a potential biomaterial for cartilage replacement [64].

The synthesis of novel 2D, nano lamellar materials enabled fresh lubricating oils with lamellar additives to enhance lubricity. Mxenes are one such 2D lamellar material (carbides, nitrides, and carbonitrides) [68] discovered in 2011 [69] and possess excellent anti-friction characteristics [68]. Thus, their characteristics as nano-additives in lubricants have recently been studied. In 2021, Zhang et al. [68] studied the tribological behavior of the steel tribo-couple (ball-on-disk) lubricated by liquid paraffin oil having MoS_2/Mxene composite additives. The tribological properties of paraffin oil containing MoS_2/Mxene composite additives are better than that of pure paraffin oil. The distinctive microstructure of MoS_2/Mxene heterojunctions aids the formation of tribo-film (figure 10), which constitutes the underlying tribo-mechanism. The upper right inset (figure 10) schematically shows the dispersion of MoS_2/Mxene in the oil.

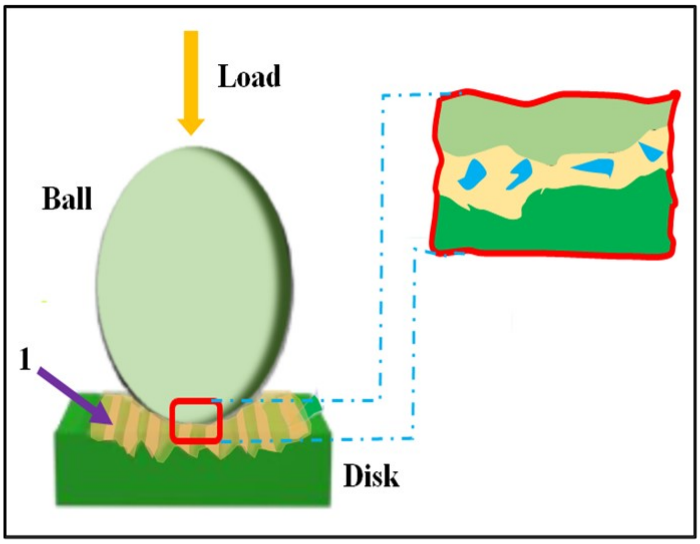

Figure 10. Schematic of the tribo-couple lubricated by paraffin oil containing MoS_2/Mxene nano additives (1. MoS_2/Mxene tribo-film) (upper right inset schematically showing the dispersion of MoS_2/Mxene in the oil) (adapted from [68]).

In the past few decades, the development of high-resolution electron microscopy aided in depicting the morphology of the biological structures accurately, enabling their mimicking on inorganic materials. The contact surfaces are textured to mimic the biological structures [62], and the biomimicked textures improve the adhesion and friction for gripping and climbing [62]. Furthermore, the in situ electron microscopy facilitates real -time characterization of wear mechanisms induced on the tribo-couple during the tribo-tests. In 2012, using in situ scanning electron microscopy (SEM), Heinrichs et al. [71] studied an aluminum tip passing over the polished tool steel flat (figure 11(a)). The tip plastically flattened immediately after the contact against the flat (figure 11(b)), leading to adherence of aluminum onto the flat (figure 11 (c)).

The typical tribological wear mechanisms are used to identify the specific damage patterns on the ground stone tool surfaces; thus, emerged archaeotribology. In 2014, Adams [63] summarized the experimental and characterization techniques used to analyze ground stone tools and emphasized the standardization of use-wear patterns. By relying on the studies of different tribologists, the use-wear patterns formed on ground stone tools due to different wear mechanisms are recognized and standardized. The wear mechanisms identified on the ground stone surfaces are adhesion, abrasion, surface fatigue, and tribo-chemical interactions.

The research on the interaction between triboelectricity and the semi-conductor paved the way for the emergence of a novel domain. Consider two heterogeneous materials with contact electrification in between them [72]. Separating these materials induces a potential difference. This phenomenon is the primary motivating force for energy conversion, due to the development of triboelectric nanogenerators. The coupling of triboelectricity with the

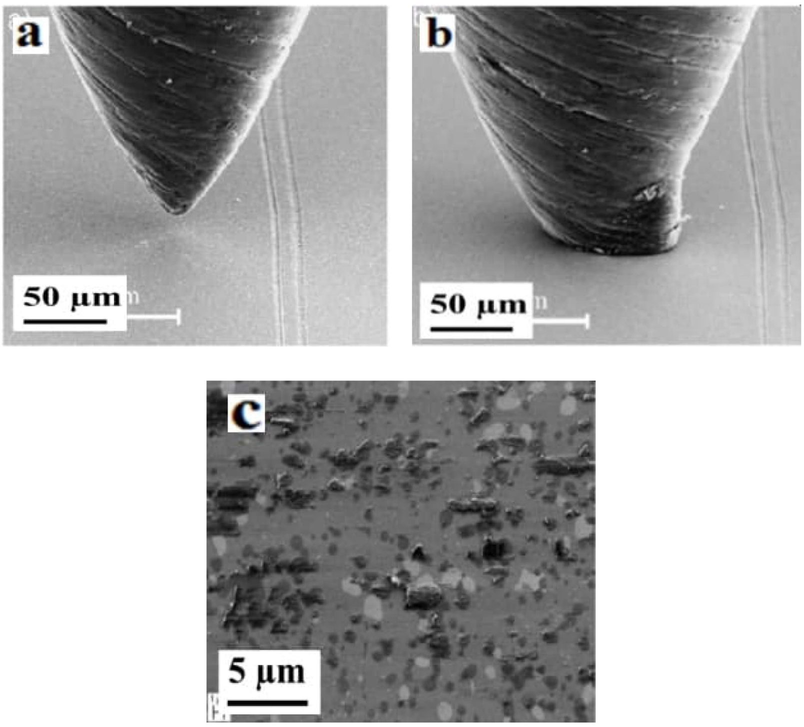

Figure 11. In situ SEM micrographs of aluminum tip and polished tool steel flat tribo-couple: (a) before contact, (b) plastically deformed tip immediately after the contact, and (c) aluminum adhered on the polished tool steel flat. Reprinted from [71], Copyright (2021), with permission from Elsevier.

semiconductor gave rise to the field of tribotronics, proposed in 2014, which covers the details of devices developed using the electrostatic potential. The triboelectrification creates the electrostatic potential as a 'gate' voltage. This 'gate' voltage controls the semiconductors' electrical transformation and transport phenomena.

2.9.2. Emphasis on sustainable tribology research

The Kyoto Protocol called for reducing greenhouse emissions that propel the drastic, aversive climate change [73]. In the case of tribology, sustainable, eco-friendly research towards friction, wear, and lubrication (green tribology) became a critical motto, and it aims to attain the social progress of the masses by enhancing the quality of their life [74]. Sustainable tribology emphasizes that the solutions determined for the problems concerning tribology should protect the environment by promoting efficiency, durability, affordability, and minimum raw material and energy consumption [74]. Sustainable tribology research reduces fuel usage and gases (greenhouse) discharge and enhances the quality of human life [15]. The dedicated practice of sustainable tribology research leads to the sustenance of mother earth (figure 12).

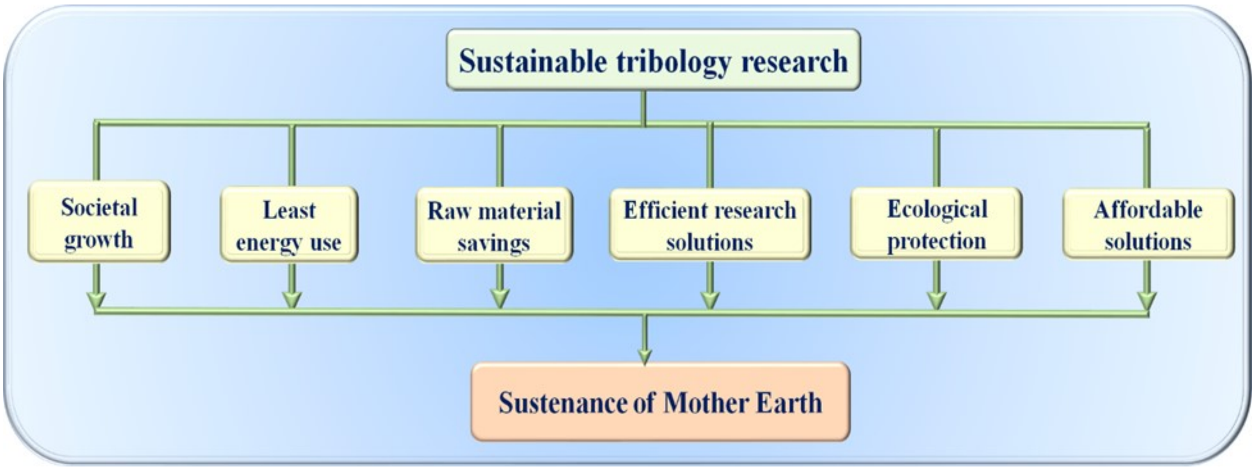

Figure 12. The elements of sustainable tribology research promoting the sustenance of mother earth.

3. Summary

In the Paleolithic era, humans made the fire, inadvertently utilizing the frictional heat, and the Upper Paleolithic inhabitants skillfully fabricated an ornament through grinding, carving, boring, drilling, and polishing processes. Furthermore, they made holes on the incisors, removed the infected pulp, and filled the holes, advantageously utilizing the wear process. The Neolithic humans removed tooth material through in vivo drilling. Lubrication was practiced in ancient Egyptian civilization, where water was used as a lubricant, eased the transportation of statues. The friction coefficient of tribo-couple (wet sand and sled) is lower than that of the dry sand and sled tribo-couple, resulting in conducive conditions for sled dragging. The industrial revolution era witnessed the formulation of lubricating animal or vegetable oils with additives, Euler's work on static and kinetic friction, and Coulomb adding the third rule to the classical laws of friction, Amontons formulated in the pre-industrial era. Significant progress has been made in the scientific era by discussing friction, wear-inducing mechanisms, and lubrication phenomenon. Lately, interdisciplinary tribology research has gained significant traction with novel studies reported on interdisciplinary domains, such as biomimetic tribology, archaeotribology, biotribology, and food tribology.

In summarizing, tribology is evolved a long way from Paleolithic humans unknowingly using sliding friction to the contemporary tribologists analyzing endoscopy-induced friction. Hence, the progress in tribology contributes to continuously improve the quality of human life, which forms the uniqueness of tribology research.

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