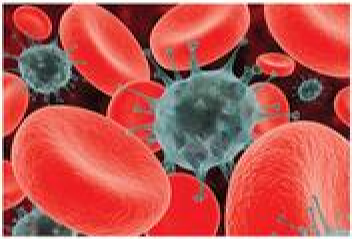
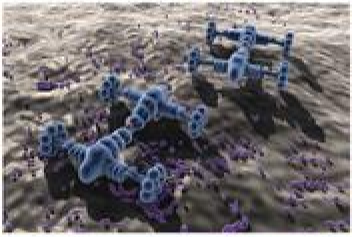
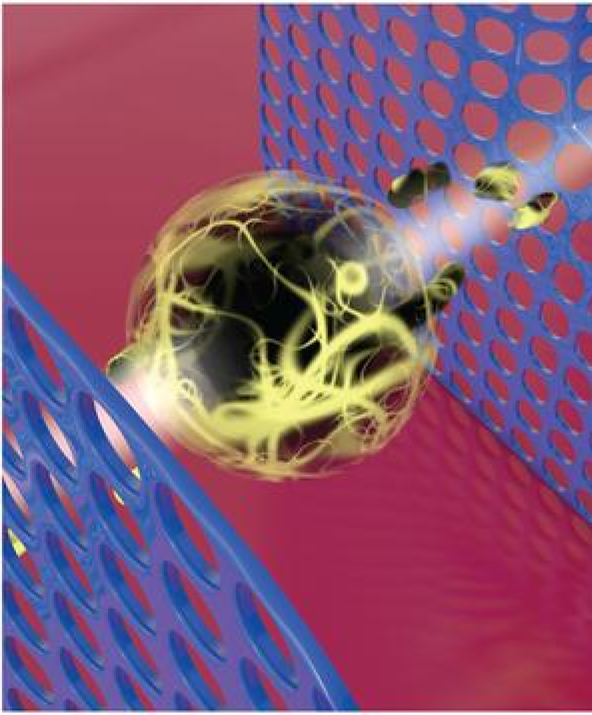
CRC Concise Encyclopedia of NANOTECHNOLOGY







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Nanotribology: Green Nanotribology and Related Sustainability Aspects

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CONTENTS

INTRODUCTION

Man-made machines on all length scales dominate current human lives. Technology and our current ways of dealing with resources, the transport of materials and products, manufacturing of products, and finally the disposal or reuse or recycling of products are increasingly getting green and, even more so, aim at sustainability.

People have realized that we live on a planet with boundaries, and our approaches have changed accordingly. Tribology is represented in most machines, since most machines are devices with moving parts, interacting parts in relative motion—and thereby tribosystems. With the recent rise of micro- and nanoscale technologies, micro- and nanotribologies are increasingly important and need to be included in green technology approaches. Even more so given the great future that is forecasted for nanotechnology, for which nanotribology is an enabling technology.

Green technology is understood as technology that is "better than currently used ones" or technology "regarding green applications" (such as renewable energy). Such an understanding of *green* is different from the understanding of *sustainable*, which is a more holistic concept. The technology of palm oil–based engines is a simple example illustrating the difference between green and sustainable technology. It is green technology, because such engines use vegetable oil rather than fossil fuels, and thereby have a closed carbon circle, but it is not sustainable technology, due to the usage of a substance as fuel that can also be used as cooking oil (feeding the needy) and due to the contribution of oil palm plantations to the destruction of ancient rainforest and decrease of biodiversity (which are both complex systems influencing the living conditions of future generations). Sustainable technology complies with the principles of social, economic, and ecological sustainability. It takes into consideration also future generations and their needs and good living (Robbins 2011).

The following sections define tribology and nanotribology and subsequently introduce concepts of green technology and sustainable technology, first on their own and second as concepts related to nanotribology. This way of introduction and subsequent interweaving of previously unrelated concepts allows the reader to understand the key contributing fields and the timeline in the development of green nanotribology and related sustainability aspects, bridging historic trends and current developments, accumulating in an emerging field that increasingly gains importance.

TRIBOLOGY

H. Peter Jost, president of the International Tribology Council, coined the word tribology in the year 1966. The word is a combination of τρίβω, tribo, "I rub" in classic Greek and the suffix -logy from -λογία, -logia "study of," "knowledge of." Various reports published between 1966 and 2009 for the United Kingdom and for China state that between 1% and 2% of the gross national product or gross domestic product could be saved by optimized tribology (Jost 1966, Research Report Tribologie 1976, Tribology Science Industrial Application Status and Development Strategy 2008, Zhang 2009).

In the systems science tribology, also the environment and development with time have to be accounted for; therefore, tribology and especially the emerging fields of micro- and nanotribologies (which are close in scale of action to the functional units of the green and in most cases sustainable living tribosystems) are well suited for the development and successful implementation of green and sustainable concepts.

NANOTRIBOLOGY

The term "nanotribology" was introduced in the year 1991 by Krim and coworkers in the scienti c journal *Physical Review Letters* with their study on atomic scale friction of a krypton monolayer (Krim et al. 1991). Nanotribology denotes the study of tribologically interesting materials, structures, and processes with methods of nanotechnology (e.g., high-resolution microscopy). This eld is of utmost importance to tribology in general, because the real area of contact between two surfaces can be very small: Rigid surfaces, for example, only touch at asperities, where extreme conditions can appear. Since the late 1980s, measurement methods have been established and are now well introduced to the scienti c and engineering community that allow to obtain data on interactions that take place on such a small scale. Prominent examples for such measurement devices are scanning probe microscopy and nanoindentation techniques that can probe interactions on smallest scales (subnanometer distances, one atom thin separations, monomolecular lubricant layers). Atomic force Kelvin probe microscopy is, for example, used for the measurement of surface charges, and friction force microscopy can measure stick–slip interactions of single atoms with a crystalline surface. Because of the inherent connection of the macro- via the micro- to the nanoscale, the elds of micro- and nanotribology are of relevance for tribology at all scales (Tomala et al. 2013). One example are hip implants, where nanoscale roughness can dramatically in uence the formation of bacterial bio lms on implant surfaces inside the human body, thereby increasing the risk of in ammation and necessity of another surgery. With the development of micro- and nanomachines (such as microelectromechanical systems [MEMS] and nanoelectromechanical systems, such as the acceleration sensor in airbags or nanoresonators), these elds are increasingly getting attention (Bhushan 2008). Important application elds of nanotribology are molecular dynamics studies, MEMS, hard disks, and diamond-like carbon research (Elango et al. 2013).

GREEN TECHNOLOGY

Technological advancement has for a long time been directly connected with human development. The late Professor Gustav Ranis, Frank Altschul Professor Emeritus of International Economics at Yale, for example, states that "human development, in combination with technology, yields economic growth which, in turn, is necessary to generate further advances in human development" (Ranis 2011). However, recently, this view started to change. Planetary boundaries (Rockström et al. 2009) and depletion of resources, combined with the knowledge that human technological, industrial, and further activities alter and change the Earth, in many cases not for the better, leading to a new view in which technological advancement is not seen anymore as directly correlated with an improvement of the human condition—it is now clear that besides technology, the society and the environment also need to be integrated. The planetary boundaries concept (Figure 529 and Table 127) introduced by Johan Rockström, the executive director of the Stockholm Resilience Centre, and coworkers in *Nature* in 2009 and further elaborated in a report to the club of Rome (Wijkman and Rockström 2012) is a new approach to de ning biophysical preconditions for human development: they de ne the safe operating space for humanity with respect to the Earth's system. Earth is a complex system full of interdependencies and interconnectedness that reacts in nonlinear, often abrupt ways, and human actions are the main driver of current global environmental change. We rely on the relative stability of this system and many of its subsystems (such as the monsoon system).

Green technology is de ned as technology with less impact on the environment than traditionally used technology and as technology that contributes to green applications such as renewable energy (for example to friction and wear issues in wind turbines). Keywords regarding green technology comprise life cycle assessment, green manufacturing, ecological design, green chemistry, industrial symbiosis (employs principles of ecological systems to industrial systems), ecological modernization (true green technology, disruptive technologies, e.g., new bioinspired approaches without the use of plastics or metals), and integrating concepts and frameworks at the interface of technology, society, and the environment (Robbins 2011).

Si-wei Zhang, past president of the Chinese tribological society, introduced green tribology as an international concept in the year 2009. Green tribology is the science and technology of tribological aspects of the ecological balance and their in uence on the environment and living nature (Nosonovsky and Bhushan 2010, Nosonovsky and Bhushan 2012). Tribology must proceed in consensus with the most important worldwide rules and regulations concerning the environment and energy.

SUSTAINABLE TECHNOLOGY

The concept of "green" is not the same as the concept of "sustainable." Green refers to "better for the environment than conventional" or "related to green applications." The concept of sustainability emerged in the 1980s, when the United Nations published the Brundtland report (World Commission on Environment and Development 1987) and de ned sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." The Brundtland report states: "In essence, sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations." Sustainability is now a widely used word, and depending on which group uses it, it can denote very different concepts. Here, in this chapter, sustainability is used in its original de nition

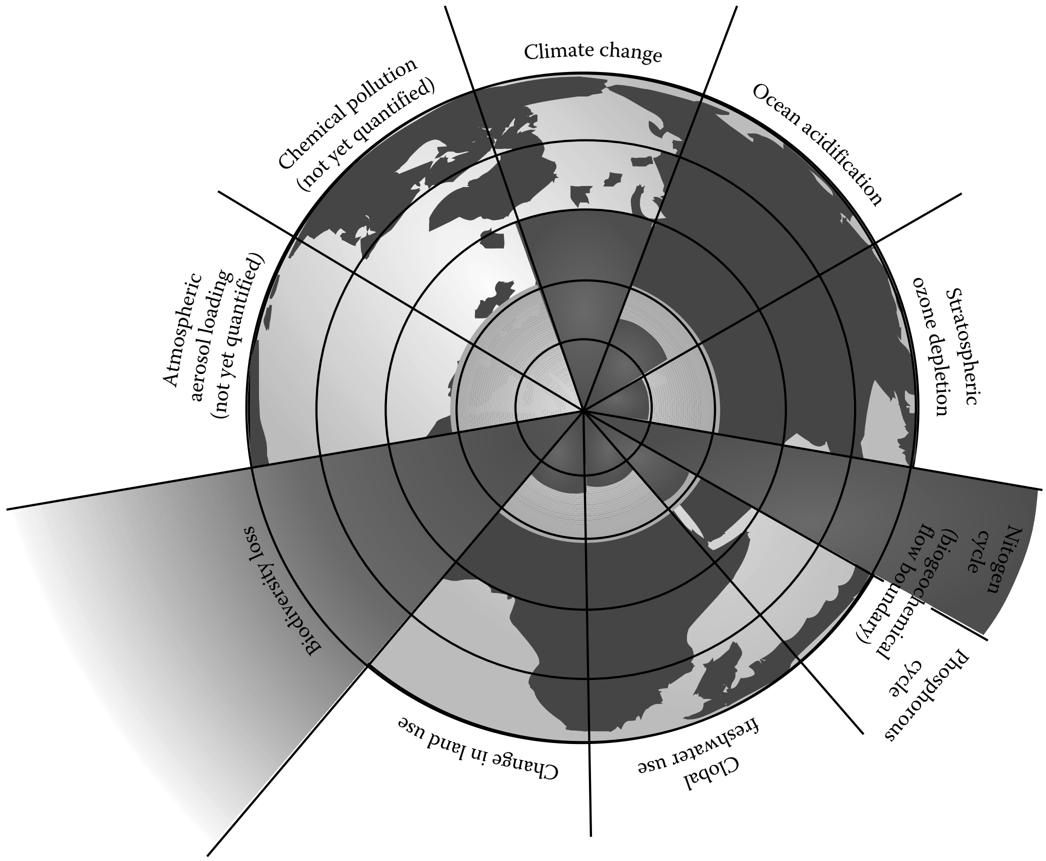

FIGURE 529 The planetary boundaries for Earth (Rockström et al. 2009). Inner circular shading: safe space. Wedges: estimates for the current position. Note that the boundaries in three systems (rate of biodiversity loss, climate change, and human interference with the nitrogen cycle) have already been exceeded. Image Copyright (2009) Nature Publishing Group. Reproduced with permission.

from the Brundtland report and thereby related to economic well being, environmental protection, and social equality.

Examples for sustainable technologies with relevance for tribology are alternative fuels (such as biodiesel, bioalcohol, nonedible vegetable oil, and nonfossil methane and natural gas), electric cars, energy recycling, environmental technologies (such as renewable energy, water puri cation, air puri cation, sewage treatment, environmental remediation, solid waste management, and energy conservation), hydropower, manure-derived synthetic crude oil, soft energy technologies, water power engines, wave power, and windmills. For more in-depth information on the connections and interdependencies of technology, globalization, and sustainable development, the reader is referred to Ashford and Hall (2012).

GREEN NANOTRIBOLOGY

Green nanotribology is green technology dealing with friction, adhesion, wear, and lubrication of interacting surfaces in relative motion at the nanoscale. A smart combination of mechanical, energetic, and chemical approaches, combined with optimum designed materials, and minimized stresses to the environment and biology, paths the way toward green nanotribology.

Green nanotribology includes biomimetic tribological nanotechnology; sustainable control of friction, adhesion, wear, and lubrication on the nanoscale; environmental aspects of nanoscale lubrication layers; environmental aspects of nanotechnological surface modi cation techniques; and nanotribological aspects of green applications such as arti cial photosynthesis. Green nanotribology shall be able to provide technical support to the preservation of resources and energy.

The components of green nanotribology (Gebeshuber 2010, Gebeshuber 2012) are nanostructured surfaces, nanoagents (ingredients, additives, products of the additives, and by-products that appear in the system after the technological application), and nanoprocesses (see Table 126).

GREEN NANOTRIBOLOGY AND RELATED SUSTAINABILITY ASPECTS

Tribologists are already used to the inherent interconnectivity of various aspects of their profession, and it is easier for them to adopt new holistic concepts such as green and sustainable as opposed to most other people working in technology elds.

In 2006, the eminent tribologist Prof. Wilfried Bartz, published an article in the scienti c journal *Tribology International* on Ecotribology. He relates environmentally acceptable tribological practices to saving of resources of energy and reducing the impact on the environment (Bartz 2006). In a now classic

TABLE 126
Nanotribology Components, Their Importance, and Points to Address for Going Green

Nanotribology	Importance	Points to Address
Nanosurfaces	Medium	Nanostructured surfaces Hierarchical surfaces Material selection Coated materials Monomolecular lubricant layers
Nanoagents	High	Physical properties Chemical properties Effect on environment and organisms Changes of properties with time Changes of properties in the triboprocess
Nanoprocesses	Medium to low	Energy ef ciency Share between process relevant energy, destructive energy, and waste as well as reusable energy Effectiveness of reusing process energy

Source: Gebeshuber, I.C., Green nanotribology and sustainable nanotribology in the frame of the global challenges for humankind, in: *Green Tribology—Biomimetics, Energy Conservation, and Sustainability*, Bhushan B. (ed.), Springer, Heidelberg, Germany, 2012, pp. 105–125.

illustration, the ecobalance tree, Bartz mentions important parameters that need to be taken into consideration in the development of ecotribology: the raw material, its transport, the production of products using materials, the transport of these products, the usage, and the disposal. Important aspects are the exploitation of resources, waste management, emissions, recycling, combustion, and reusage.

Sasaki's 2010 article on environmentally friendly tribology (Ecotribology) in the *Journal of Mechanical Science and Technology* focuses mainly on progress through surface modi cation (Sasaki 2010).

Tzanakis and coworkers highlight future perspectives of sustainable tribology in their 2012 article in the *Renewable and Sustainable Energy Reviews* (Tzanakis et al. 2012). They present three interesting case studies from diverse areas of interest in tribology (micro-CHP (combined heat and power) systems, slipways for lifeboats, recycled plastics for skateboard wheels) and perform tribological analyses and sustainability considerations.

Gebeshuber introduced sustainable nanotribological systems based on the sustainability concept of design lectures from living nature, the principles of life as introduced by the Biomimicry Guild in 2009 (Gebeshuber 2012, Figure 530). The six basic categories are "survival because of evolution" (in the context of sustainable nanotribology, this means continuous incorporation and anchoring of information), resource ef ciency regarding material and energy (closed tribosystems, recycling and reuse of substances and waste energy), adaptation to changing conditions (reactive nanosurfaces, nanoagents, and nanoprocesses that change depending on the environment and that are used in as small amounts as necessary), integration of development with growth (in the context of sustainable nanotribology, this means achieving a balance between development and growth), responsiveness and being locally attuned (tribological systems not as good as possible, but as good as necessary, with additional bene ts regarding energy savings and environmental compatibility), and the usage of life-friendly chemistry (water-based chemistry, green chemistry—one of the basic requirements of green nanotribological systems) (Table 127).

OUTLOOK

Green and sustainable nanotribologies are currently relatively small elds that act as enabling technologies for nanotechnology in general. Optimized nanotribological systems where from the very beginning concepts of sustainability are integrated can pave the way for sustainable nanotechnology

FIGURE 530 Green and sustainable nanotribologies, word cloud constructed from Gebeshuber 2012.

TABLE 127
Contributions of Green Nanotribology to Address Issues Arising from the Nine Planetary Boundaries

Planetary Boundary	Green Nanotribology Solutions
Climate change	Energy materials with optimized tribological performance; reduced information and communication technology (ICT) global greenhouse gas emissions by optimized micro- and nanomechanics; less CO_2 waste of machines due to optimized tribology (less fuel consumption in production and use).
Rate of biodiversity loss	Less consumption of resources via optimized nanotribology in production and use allows for less deforestation and more places for wildlife to thrive.
Interference with the nitrogen and phosphorus cycles	Optimized nanotribosystems with reduced NO_x and phosphate emissions.
Stratospheric ozone depletion	Usage of non ammable, non-ozone-depleting solvents.
Ocean acidi cation	Less CO_2 waste of machines due to optimized tribology (less fuel consumption in production and use).
Global freshwater use	Optimized nanotechnological desalination processes, wastewater treatments, and sewage treatments.
Change in land use	Optimized nanotribological systems for optimized land use (more ef cient production, storage, novel batteries that take less space, etc.).
Chemical pollution	Reduced lubricant spillage by usage of molecularly thin lubricant lms instead of bulk lubrication.
Atmospheric aerosol loading	Optimized machines giving off less small wear particles and less polluting exhaust fumes.

Note: See Figure 529.

that improves the human condition and the condition of the environment around us and that provides a technological environment that grants freedom to pursue long-term social and economic development.

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