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H. Inter – and Transdisciplinarity in Science and Technology

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Terminology and standards in research at nano level

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Abstract. This paper discusses the terminology used at nano level concerning materials, technology and characterization, to promote adequate vocabulary and definitions, as recognized in international standards and reference works. The ISO Technical Committee for Nano Sciences 229 has pointed out current ISO standards related to terminology in this active field of research and applications. Research and applications involving the nano level, often referred to as nanoscience or nanotechnology, involves the study and manipulation of materials at the atomic, molecular and macromolecular scale, typically between 1 and 100 nanometers. There are discussed aspects characterizing this emerging domain: size and scale, material properties, interdisciplinarity of research and nano technologies, techniques and equipment for investigations, fabrication methods, new processes and applications, challenges, regulation and standardization. Because elf the authors’ specialization, the discussions are related especially to mechanical engineering and less for chemical aspects at nano level.

Keywords: terminology, nano object, nanostructure, nanotechnology, standardization.

1. Events in the history of nanotechnologies

In 1940, the International Federation of National Standardization Associations (known as ISA) recommended the prefix “nano-” with reference to 10^{-9}, one of the last decisions of an ISA technical committee. A half-century later, this prefix would

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be used to name “one of today’s most active industrial frontiers, nanotechnology” [1].

The terms "nanotechnology" and "nanomaterial" have specific origins and histories.

The term "nanotechnology" was first used by Norio Taniguchi in 1974. This professor at Tokyo Science University has defined nanotechnology as "Nanotechnology mainly consists of the processing of separation, consolidation, and deformation of materials by one atom or one molecule." His work focused on the precision machining of materials at the nanometer scale [2]. Other specialists use terms like “nanomanufacturing” (but the authors consider the definition given in [3][1] to be too restrictive), “nanofabrication”, nanoprocessing or nanoscale engineering. Taking into account [4]-[7], we consider nanomanufacturing a process of producing nanoscale materials, structures, devices and systems in a repeatable, scalable, and cost-effective manner. It includes techniques like self-assembly, lithography etc. Based on [8]-[10]. Nanofabrication could be defined as the process of designing and constructing/building/producing devices or structures on a nanometer scale (1-100 nm). It involves techniques and processes such as lithography, etching, and deposition, enabling the creation of nanoscale features. Nanoscale engineering [11]-[13] implies the design and the fabrication of products that involve nanomaterials and nanoprocesses. It involves controlling the properties and behaviors of materials at the atomic or molecular level to develop innovative technologies with enhanced or novel functionalities, often used in electronics, medicine, and energy applications.

The term "nanomaterial" was popularized later, as the field of nanotechnology developed. While there isn't a single pinpointed first use of "nanomaterial," it became widely recognized in the 1980s and 1990s with the advent of significant discoveries in nanotechnology. For example, the discovery of fullerenes (buckminsterfullerene, C60) by Kroto, Smalley, and Curl in 1985 brought attention to materials at the nanoscale, and the term "nanomaterial" started to gain traction as researchers began to systematically explore materials with nanoscale dimensions [14].

These milestones marked the formal introduction and popularization of the concepts of nanotechnology and nanomaterials, setting the stage for the rapid development of the field in subsequent decades.

In 2017, Maria Lazarte and Elizabeth Gasiorowski-Denis, 2017 published „Silent game changers of the tech revolution*” [15], including among them, the 3D printing, renewable energies, nanotechnologies.” When nanotechnology first became popular in the 1980s to the early 21st century, it caused much controversy and fear*. This uncertainty often makes investors wary of unknown technologies,

[1] ”Nanomanufacturing is a type of manufacturing process involved in the production of nanoscale materials that can either be fluids or liquids. It is also used in the manufacture of parts top-down in small steps to ensure high levels of precision or bottom-up from nanoscaled materials. Nanomanufacturing is used in various technologies including etching and laser ablation, among others. Nanomanufacturing and molecular manufacturing are very different.” [3]

but ISO[2] standards can allay some of these doubts and bolster trust by setting parameters to guide safety and test quality. The group of experts in ISO/TC 229, Nanotechnologies [16], have been working on such standards for some time". The authors pointed out that is not in the society progress not to have standards on emerging subject in industry, transport and research, because this could encourage the emergence of parallel systems, added complexity and unnecessary waste, in contrast with the necessary objective of sustainability. But standards should be flexible, adaptive and non-resistant to innovation and thus, they will be one of the silent game changers in human society. This conclusion reminds us the title of the well-structured history of ISO, "The International Organization for Standardization (ISO), Global governance through voluntary consensus" [1], and the role of standardization organizations "as facilitator of essential technical infrastructure, "this silent but all-pervading process" [17] for the global economy and the future of ISO in a changing and increasingly globalized world."

2. Introducing characteristics of research at nano level

Research at the nano level, often referred to as nanoscience or nanotechnology, involves the study and manipulation of materials at the atomic, molecular and macromolecular scale, typically between 1 and 100 nanometers. Nanoscience and nanotechnology imply the involvement of fundamental sciences but also engineering and fabrication sciences [18].

Key aspects and characteristics of research at the nano level include:

- **size and scale:**
  - nanoscale dimensions: this field, including research, technologies and applications, focuses on materials and structures with dimensions in the range of 1-100 nanometers;
  - quantum effects: at this scale, they become significant, influencing the properties and behavior of materials (but these are not the subject of this paper; the terminology for this subject is treated in a standard proposal, ISO/AWI TS 80004-12 Nanotechnologies. Vocabulary. Part 12: Quantum phenomena in nanotechnology [19],
- **material properties**
  - unique particular and often enhanced properties: nanomaterials often exhibit unique optical, electronic, mechanical and chemical properties as compared to their bulk counterparts; literature offers books on nanomaterials with particular applications, from nanocomposites [20], to anticorrosive nanomaterials [21]; the terminology for particular nanomaterials is proposed [22] or even it is already adopted in ISO standards [23],
  - surface area: nanomaterials have a high surface area to volume ratio, which can enhance reactivity and interaction with other materials,

[2] ISO – International Organization for Standardization

- **interdisciplinarity of research**
  - multidisciplinary collaboration is necessary to integrate nanomaterials and nanotechnologies in design: nanotechnology integrates principles from physics, chemistry, biology, materials science and engineering, even law regulation when processes involve operator's security and environment protection; for instance, in Figure 1, "computer science" is included in order to motivate scientists to use and to develop techniques of computational intelligence for nanomaterials and nanotechnologies [24], including molecular modeling, simulation of nanodevices' behavior, high performance computing (statistics, nanoparticles analysis etc.), genetic algorithms for optimization, neural network for establishing the influencing factors for a process or a system etc.,
  - cross-disciplinary applications that span various fields, including medicine, electronics, energy and environmental science. Many interdisciplinary sciences have the prefix nano to attention specialists that phenomena and processes involve nano scale, for instance, nanomedicine, nanotribology [25]-[27].
- **techniques, methodologies and equipment**
  - advanced characterization equipment [28]-[30]: techniques such as atomic force microscopy (AFM), scanning tunneling microscopy (STM), and transmission electron microscopy (TEM) are essential for studying nanomaterials,
  - fabrication methods: methods like chemical vapor deposition (CVD), molecular beam epitaxy (MBE), and electron beam lithography are used to create nanostructures,
- **novelty in using such materials and technologies**
  - new phenomena and processes: properties like superparamagnetism, quantum confinement, and plasmonics are unique to nanomaterials.
  - innovative applications: development of innovative technologies such as nanoscale transistors, drug delivery systems and nanosensors,
- **challenges**
  - scalability: translating lab-scale synthesis and applications to industrial-scale production can be challenging and sometimes tricky,
  - safety and ethical issues: potential health and environmental impacts of nanomaterials need thorough assessment and regulation,
- **precision, control and repeatability**
  - atomic precision: research aims to manipulate matter with atomic precision, allowing the creation of materials with expertly tailored properties, but the reliability of the designed systems with nanoscale characteristics is far for being acceptable,

  - self-assembly: utilizing the principles of self-assembly to create organized nanostructures.
- **fundamental research and theoretical modeling**
  - theoretical models: scientists try to develop models for predicting the behavior of nanomaterials and understand their fundamental properties,
  - experimental validation: conducting experiments for validating theoretical predictions and discovering new phenomena and processes.
- **innovative measurement techniques**
  - non-destructive techniques: employing non-destructive techniques to study nanomaterials without altering their properties; the necessary equipment could be adapted to actual-time observation, helping researchers to understand the material behavior and to use their conclusions in actual applications,
  - in-situ analysis: performing analysis in real-time under operating conditions to understand dynamic processes at the nanoscale.
- **regulation and standardization**
  - standards development: creating standards for nanomaterial characterization, measurement, and safety,
  - regulatory frameworks: setting up guidelines for the safe development and use of nanotechnologies.

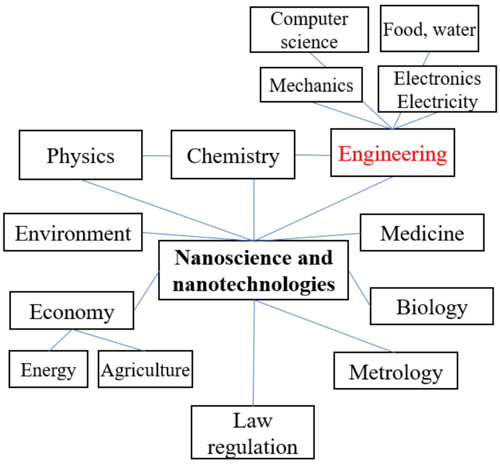

Fig. 1. Multidisciplinary and interdisciplinarity of nanoscience and nanotechnologies.

Figure 2 presents a classification of nanomaterials having as criteria their shape and the application field, but having details for engineering, introducing metrology in the nanofield as associated equipment for measuring and investigating nanomaterials and nanoprocesses has boosted innovations in nanotechnologies.

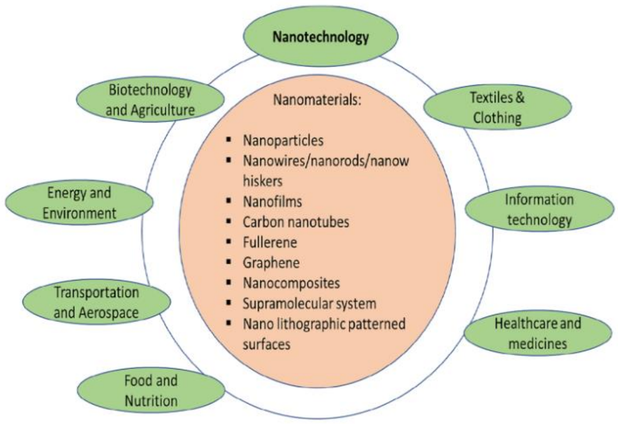

Fig. 2. Classification of nanomaterials and applications [18].

Of course, nanoparticles could be divided into subgroups: spherical, nanosheets (like graphene, graphene oxide, hexagonal boron nitride), rolled, beans etc.

Research at the nano level is characterized by its ability to revolutionize existing technologies and create entirely new fields of application, driven by the unique properties and behaviors of materials at the nanoscale. Figure 3 presents several features of this research field.

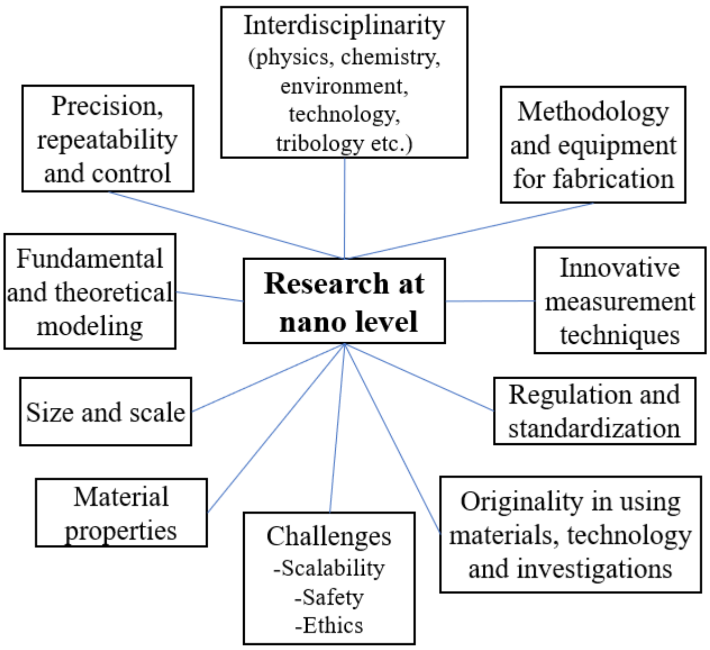

Fig. 3. Particular aspect for research at nano level.

As one may notice, the research and achievements at nano scale urge the development of creating standards for nanomaterials and their characterization in order to analyze and compare the results of different research teams, but with the same objectives.
Of course, considering the authors' specialization of, mainly mechanical engineering, the examples will be discussed mostly from this field.

3. A SWOTT analysis of nanosciences and nanotechnologies

A SWOTT analysis (Strengths, Weaknesses, Opportunities, Threats, and Trends) of nanosciences and nanotechnologies provides a structured framework to evaluate the current state and future prospects of this field.

Strengths

- **unique properties**: enhanced physical, chemical, and biological properties at the nanoscale and high surface area to volume ratio improves reactivity and efficiency.
- **interdisciplinary applications**: broad applicability across medicine, electronics, energy, and environmental sectors and the ability to innovate and improve existing technologies.
- **precision and control**: atomic and molecular level control leads to highly customized and efficient materials and devices and advanced fabrication and characterization techniques enable detailed study and manipulation.
- **economic potential**: potential to drive economic growth through new products and industries and opportunities for high-value products and processes.

Weaknesses

- **scalability**: difficulty in scaling up from laboratory research to industrial production and prohibitive costs of production and fabrication techniques.
- **technical challenges**: complex and expensive equipment needed for nanoscale research and challenges in keeping stability and reproducibility of nanomaterials,
- **regulatory hurdles**: lack of standardized regulations and guidelines for the use of nanomaterials and uncertainty in long-term safety and environmental impact.
- **public perception**: limited public understanding and acceptance because of lack of information and education and concerns over potential risks and ethical issues. Books like [31]-[34] cover the basics of nanoscience, the potential applications of nanomaterials, and the societal and ethical implications of this emerging field. It's a brief read that does not require prior technical knowledge, making it perfect for beginners.

Opportunities

- **medical advances**: development of targeted drug delivery systems, improved diagnostic tools, and regenerative medicine and potential for personalized medicine and advanced therapeutic techniques.

- **sustainable technologies**: innovations in renewable energy (e.g., solar cells, fuel cells, and batteries) and environmental applications such as water purification, pollution control, and efficient resource utilization.
- **electronics and computing**: creation of faster, smaller, and more efficient electronic devices and advances in quantum computing and nanophotonics.
- **new markets and industries**: potential to create entirely new industries and markets and opportunities for startups and small businesses to innovate.

Threats

- **health and environmental risks**: uncertainties about the toxicity and long-term environmental impact of nanomaterials.
- potential for unforeseen adverse effects on health and ecosystems.
- **regulatory and legal barriers**: stringent regulations could hinder innovation and commercialization and intellectual property challenges and disputes.
- **economic and market risks**: high costs may limit adoption and accessibility and market volatility and competition from established technologies.
- **ethical and social issues**: concerns about privacy, security, and ethical implications of advanced nanotechnologies and potential for misuse or dual-use in harmful applications.

Trends

- **increased investment and funding**: growing investment from both public and private sectors and increased funding for research and development.
- **advances in fabrication and characterization**: continuous improvement in techniques for fabricating and analyzing nanomaterials and development of more affordable and scalable methods.
- **collaboration and interdisciplinary research**: enhanced collaboration between academia, industry, and government and interdisciplinary research initiatives driving innovation.
- **standardization and regulation**: efforts towards developing international standards and regulatory frameworks and focus on ensuring safety and sustainability of nanotechnologies.
- **public engagement and education**: initiatives to improve public understanding and acceptance and educational programs to train the next generation of researchers and engineers.

By analyzing these aspects, the actants and stakeholders can better understand the current landscape and strategically plan for future developments in nanosciences and nanotechnologies.

Recently, on ISO site, Naden C. underlines that the economy comprises different players, including scientists, regulators, manufacturers and much more, so international vocabulary is essential [35]. ISO’s comprehensive 13-part series of standards for nanotechnology is a globally used tool that offers exactly that, and it has recently had some revisions and updates.

4. Differences in standard terminology

Along with successfully surpassing hundreds of years of economic and political turmoil, humans` ever so fast industrial and technological evolution has had society facing proportional cultural, ideological and environmental shortcomings. By bridging the technological gaps between nations and unifying production, safety and academic breakthroughs, the standards have played an influential role in sustainably advancing ideas, thus attaining true, borderless progress.

In nanotechnology, terminology can vary slightly among different standards organizations, leading to differences in definitions and nomenclature. Below are some examples of standard terminologies for "nano-terms" (terms used in nanoscience and nanotechnology) as defined by various standards organizations, along with references. We describe three specific terms: nano-object (Table 1), nanostructure (Table 2), nanotechnology (Table 3).

Table 1. Definition of nano-object

		Definition	Examples
ISO	ISO/TS 80004-1:2015 [37] ISO/TS 80004-1:2023 [38] ISO/TS 80004-2:2023 [39]	A material with one, two, or three external dimensions in the nanoscale (approximately 1 nm to 100 nm).	• nanoparticles (with all three dimensions in the nanoscale), • nanofibers (two dimensions in the nanoscale), • nanoplates (one dimension in the nanoscale).
IEC	IEC TS 62607-2-1:2017 Part 2-1: [40]	A discrete piece of material with one, two, or three external dimensions in the nanoscale.	Similar to ISO's definition, it includes nanoparticles, nanorods, and nanoplates, but with a focus on their discrete nature as individual entities
ASTM	ASTM E2456-06 [41]	A material with any external dimension in the nanoscale or having internal structure or surface structure in the nanoscale	This broader definition includes particles, rods, fibers, and composites with nanoscale features.
IUPAC	IUPAC Compendium of Chemical Terminology (the "Gold Book") [42]	An object that has one, two, or three external dimensions in the nanoscale, with specific characteristics that are size-dependent.	Includes structures like nanospheres, nanowires, and nanodiscs, emphasizing size-dependent properties

On the ISO official website, 131 standards have “nanotechnologies” in their title. This stands for only 0.51% out of 25508 ISO standards, in august 2024 [36]. ISO and IEC[3] specifically adopted the external dimensions to be within the nanoscale. ASTM[4] includes both external and internal structures, expanding the scope to materials with nanoscale features, not just dimensions. ISO and IEC emphasize

[3] IEC – International Electrotechnical Commission

[4] ASTM – American Society for Testing and Materials; from 2001 – ASTM International

discrete entities (individual nano-objects). ASTM has a broader approach, encompassing any material with nanoscale features, whether discrete or composite. IUPAC[5] highlights the importance of size-dependent properties in defining nano-objects.

Concerning examples and applications, ISO and IEC examples are more focused on individual entities like particles, fibers, and plates. ASTM examples may include more complex structures like nanocomposites. IUPAC examples highlight the importance of specific characteristics related to size, such as enhanced optical or electronic properties.

Other definitions for nano-object, from recent notable books on nanotechnology are given.

- "A nano-object is a discrete piece of material with one, two, or three external dimensions in the nanoscale range (1-100 nm)" [43].

- "A nano-object is a material entity with at least one dimension in the range of 1 to 100 nanometers. Such objects can include nanoparticles, nanorods, nanowires, and nanoplates" [44].

- "A nano-object refers to an object with one, two, or three external dimensions at the nanoscale (approximately 1 to 100 nm), such as nanoparticles, nanowires, and nanotubes." [45].

- "A nano-object is defined as an object with at least one dimension in the nanometer range, generally between 1 and 100 nanometers, encompassing particles, rods, wires, and plates" [46].

- "A nano-object is any object that has at least one dimension in the range of 1 to 100 nanometers. This includes particles, wires, tubes, and other shapes that exhibit unique properties due to their nanoscale dimensions" [47].

These definitions provide a comprehensive understanding of what constitutes a nano-object, highlighting its dimensions and the types of structures that fall under this category.

In Romanian literature, there are several mentions for defining terms related to nanomaterials and nanotechnologies.

- "UN nano-obiect este un material cu cel puțin una dintre dimensiuni în domeniul nanometric (1-100 nm), cum ar fi nanoparticulele, nanofibrele sau nanofilmele"[6][48]; this definition includes the standard definition.

- "Un nano-obiect este un obiect cu una, două sau trei dimensiuni externe în domeniul nanometric, care prezintă proprietăți distincte datorită dimensiunilor sale nanometrice" [49][7].

- "Un nano-obiect este un material cu cel puțin una dintre dimensiunile externe în intervalul 1-100 nanometri, incluzând particule, tije, fibre și filme nanometrice" [50].[8]

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[5] IUPAC – International Union of Pure and Applied Chemistry

[6] "A nano-object is a material with at least one of its dimensions in the nanometer range (1-100 nm), such as nanoparticles, nanofibers or nanofilms."

[7] "A nano-object is an object with one, two or three external dimensions in the nanometer range that exhibits distinct properties due to its nanometric dimensions."

- "Nano-obiectul se referă la o structură cu una sau mai multe dimensiuni în domeniul nanometric, având proprietăți fizice și chimice unice datorită dimensiunilor sale reduse" [51].[9]

The term "nanostructure" was first introduced in scientific literature by professors Gerd Binnig and Heinrich Rohrer [52], who are credited with the invention of the scanning tunneling microscope (STM) in the early 1980s. They were awarded the Nobel Prize in physics in 1986 for their groundbreaking contributions. Their work with STM allowed scientists to visualize and manipulate structures at the atomic and nanometer scale, which led to the widespread use of the term "nanostructure" to describe materials and objects with dimensions on the nanometer scale.

While the term "nanostructure" was popularized in the scientific community during this time, it is important to note that the concept of materials and structures at the nanoscale has been implicitly present in earlier work, even if the specific term wasn't used. However, Binnig and Rohrer's contributions [52] mark the first formal usage and recognition of the term within the context of modern nanotechnology.

ASTM standards proposed a broader definition for nanostructures, including particles, rods, fibers, and composites with nanoscale features.

Table 2. Definition of nanostructure

Organi-zation	Standard	Definition	Examples
ISO	ISO/TS 80004-1:2015 [37] ISO/TS 80004-1:2023 [38] ISO/TS 80004-4:2023 [53]	A structure with at least one dimension in the nanoscale (approximately 1 nm to 100 nm), or a structure that exhibits novel properties due to its nanoscale dimensions Nanostructures can be one-dimensional (e.g., nanowires), two-dimensional (e.g., nanoplatelets), or three-dimensional (e.g., nanospheres).	• **Quantum Dots**: Semiconductor particles a few nanometers in size that have optical and electronic properties different from larger particles due to quantum mechanics • **Nanotubes**: Cylindrical nanostructures, such as carbon nanotubes, with unique mechanical, electrical, and thermal properties. • **Nanoparticles**: particles with all three external dimensions in the nanoscale; an example is a gold nanoparticle. • **Nanowires:** structures with two dimensions in the nanoscale and one dimension significantly larger. For example, silver nanowires.

[8] "A nano-object is a material with at least one of its external dimensions in the range 1-100 nanometers, including particles, rods, fibers, and nanoscale films."

[9] - "Nano-object refers to a structure with one or more dimensions in the nanometer range, having unique physical and chemical properties due to its small size." Translation from Romanian in English was done by Lorena Deleanu

Organi-zation	Standard	Definition	Examples
			• **Nanofilms** or n**anolayers**: thin films or coatings with thickness in the nanoscale, such as a nanolayer of titanium dioxide (TiO_2) on glass. • **Nanostructured materials** possess a nanoscale structure, such as porous silicon or nanostructured coatings.
IEC	• IEEE Standard 1650-2005 [54] • Adopted the ISO/TS 80004-1:2015 definition of nanostructures, emphasizing the nanoscale dimensions • IEC 62607 series) [40]	A structure with at least one dimension in the nanoscale range, typically between 1 nm and 100 nm, and which exhibits novel electronic, optical, or mechanical properties due to its size and structure.	• **Nanowires**: Extremely thin wires, often made of metals or semiconductors, that exhibit quantum effects and are used in nanoscale electronic circuits. • **Graphene**: A single layer of carbon atoms arranged in a two-dimensional honeycomb lattice, which has remarkable electrical, thermal, and mechanical properties. • **Quantum Dots**: Nanoscale semiconductor particles that exhibit quantum mechanical properties, often used in display technologies. • **Nanoscale magnetic structures**: magnetic particles or films that operate at the nanoscale, such as those used in data storage devices.
ASTM	ASTM E2456-06 Standard Terminology Relating to Nanotechnology [14]	A structure having at least one dimension in the nanoscale, typically between 1 nm and 100 nm, which can include internal or surface structures at the nanoscale, with unique properties. It emphasizes that nanostructures can be natural or engineered and include nanoparticles, nanorods, and other nanoscale materials.	**Nanocomposites**: materials composed of a nanoscale filler dispersed within a matrix, such as clay-polymer nanocomposites. **Nanoshells**: nanoscale core-shell structures, often used in biomedical applications, such as gold-coated silica nanoparticles. **Nanofibers**: fibers with diameters in the nanoscale, such as those used in filtration systems or tissue engineering scaffolds.
IUPAC	IUPAC Compendium of Chemical Terminology (the "Gold Book") [15]	An arrangement of atoms, ions, or molecules that exhibits dimensional features on the nanometer scale and which typically has specific properties arising from its nanoscale dimensions.	• **Fullerenes**: molecules composed entirely of carbon, in shape of a hollow sphere, ellipsoid or tube, such as C60, commonly referred to buckyballs, with unique chemical properties. • **Nanocapsules** used for drug

Organi-zation	Standard	Definition	Examples
			delivery, where the nanostructure can encapsulate therapeutic agents and release them at a targeted site. • **Dendrimers**: highly branched, tree-like molecules with nanoscale dimensions. • **Colloidal nanoparticles**: nanoparticles dispersed in a solution, often used in catalysis and material science.

ISO standards denominate particular aspects in nanotechnologies in ISO/TS 80004-8:2013 *Nanotechnologies. Vocabulary. Part 8: Nanomanufacturing processes* [55] and offer a guide for safety assessment and risk mitigation for technologies using nanomaterials in ISO/TS 12901-1:2024 Nanotechnologies. Occupational risk management applied to engineered nanomaterials. Part 1: Principles and approaches [56] and ISO/TS 12901-2:2014 Nanotechnologies [57]. Occupational risk management applied to engineered nanomaterials. Part 2: Use of the control banding approach). The latest standard focuses on the control banding approach to manage the risks associated with handling nanomaterials in the workplace. Another issue found in ISO/TR 12885:2018 Nanotechnologies. Health and safety practices in occupational settings [58], relevant to nanotechnologies, is the handling and disposal of nanomaterials to minimize their environmental impact, as well as protecting workers from potential exposure. An interesting aspect is related to consumers (ISO 16195:2018 *Nanotechnologies. Guidance for developing representative test materials consisting of nano-objects in dry powder form* [59]) and this standard provides guidance on developing representative test materials consisting of nano-objects in dry powder form, which are used in consumer products like cosmetics and coatings.

Table 3. Definition of nanotechnology

Organi-zation	Standard	Definition	Examples and notes
ISO	ISO/TS 80004-1: 2015 [37] ISO/TS 80004-1: 2023 [38]	the application of scientific knowledge to manipulate and control matter at the nanoscale (typically 1 to 100 nanometers) to produce novel materials, devices, and systems with unique properties Also includes the definition of n**anoscale** that refers to dimensions and tolerances of less than 100 nanometers.	Family 80004 specifies norms for different nanotechnologies
IEC	often working in collaboration with ISO, defines nanotechnology, similarly, focusing on the use of nanoscale phenomena in the design and production of materials, structures, devices, and systems. The standards emphasize the electrical and electronic applications of nanotechnology.		The IEC standards particularly address the implications of nanotechnology in the field of electrical engineering and electronics

Organi-zation	Standard	Definition	Examples and notes
ASTM	ASTM E2456-06 [41]	a branch of engineering and science devoted to the design, production, and application of structures, devices, and systems by controlling shape and size at the nanometer scale.	The definition is broad and encompasses engineering aspects of nanotechnology, highlighting its interdisciplinary nature.
IUPAC	[42]	the design, characterization, production, and application of structures, devices, and systems by controlling shape and size at the nanometer scale. Introduce the definition of **nanoscale phenomena as** the chemical and physical properties that emerge at the nanoscale, which are different from bulk materials.	This definition is consistent with IUPAC's focus on chemical and molecular science.

A step forward from nanostructures is the nanoarchitectonics [60] defined as “the integration of molecular components with strict control over the architecture and function”. This was introduced by Masakazu Aono in the second decade of third millennium [61]-[63].

Also, the term nanotechnology is defined in recently published books, trying to combine the generality with the specificity of a certain manufacturing process.

“Nanotechnology is the creation of functional materials, devices, and systems through control of matter on the nanometer length scale (1–100 nm) and the exploitation of novel properties and phenomena developed at that scale.” This definition is given by Charles Poole Jr. and Frank Owens in their book “Introduction to Nanotechnology” [44]. This definition highlights the scale at which nanotechnology operates and the importance of understanding and manipulating materials at these scales to reach novel properties and applications.

“Nanotechnology is the science and technology of materials and devices that operate at dimensions of roughly 1 to 100 nanometers. It involves the study of phenomena and the manipulation of materials at the atomic, molecular, and macromolecular scales, where properties differ significantly from those at a larger scale” [43]. This definition underlines the manipulation of matter at the nanoscale and the unique properties that emerge at these small dimensions, which can be used to create new materials and devices.

In "Nanotechnology: Understanding Small Systems" [47], Nanotechnology is described as “the engineering of functional systems at the molecular scale. It refers to the projected ability to construct items from the bottom up, using techniques and tools being developed today to make complete, high-performance products.” This statement highlights the engineering aspect of building complex systems from molecular components through bottom-up assembly.

These definitions from different books for nanotechnology provide a well-rounded understanding of nanotechnology, emphasizing its interdisciplinary nature, the focus on the nanoscale, and the novel properties and applications that arise from manipulating matter at such a small scale.

Definitions of **nanostructure**, in comparison with different standards, are presented in Table 3. While the core concept is similar across these standardization organizations, emphasizing the structure at the nanoscale (1 to 100 nanometers), there are nuanced differences in how each defines and categorizes nanostructures.
Analyzing the chosen terms, the following conclusions can be stated:

- **dimensions range**: all definitions agree that a nanostructure has at least one dimension in the nanoscale range, typically defined as 1 nm to 100 nm.
- **scope and emphasis**: ISO focuses on both the dimensional aspect and the novel properties resulting from nanoscale dimensions, ASTM emphasizes internal and surface structures at the nanoscale, in addition to the dimensional aspect, IUPAC highlights the arrangement of atoms, ions, or molecules and the specific properties arising from nanoscale features; IEEE stresses the novel electronic, optical, or mechanical properties due to the nanoscale size and structure.
- **properties**: ISO and IUPAC mention novel properties that arise from nanoscale dimensions; ASTM highlights unique properties but with an emphasis on internal and surface structures; IEEE: specifically notes novel electronic, optical, or mechanical properties.

These definitions collectively help standardize the terminology in the rapidly evolving field of nanotechnology across different disciplines and industries.
Today, sciences have a niche, a branch that added the prefix nano. Considering the authors of this paper, it is worthy to remind nanotribology and the new nano–structured materials – nanocomposites.
Nanotribology is the study of friction, wear, and lubrication at the nanoscale. It involves understanding the interactions between surfaces in relative motion and under load, at the atomic or molecular level. This field is critical for the design and development of nanoscale devices, such as microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS), where the traditional laws of friction and wear do not necessarily apply.
A recent book [64] discussed the use of nanomaterials in tribology, having as reference point the sustainability of these products and fabrication processes. Including nanomaterials in composites, lubricants, coatings and biodevices could produce synergetic effects that must be studied to direct them in a beneficial direction for users.
The applications of nanotribology include but they do not resume the followings:
- **MEMS/NEMS devices:** in micro- and nano-electromechanical systems, nanotribology is essential for ensuring the reliability and longevity of moving parts. Understanding friction and wear at the nanoscale helps in designing surfaces that minimize energy loss and prevent device failure.
- **hard disk drives:** the read/write heads in hard disk drives operate extremely close to the disk surface. Nanotribology helps in minimizing wear and friction, which is crucial for the durability and performance of these devices,
- **lubricants**: nanotribology is used to develop advanced lubricants, including nanolubricants that reduce friction and wear at the nanoscale. These are important in both industrial applications and in nanoscale machinery [65]-[67],

- **biomedical devices:** in nanomedicine, nanotribology helps in the design of medical devices that interact with biological tissues at the nanoscale, such as stents and implants, to ensure they operate smoothly without causing damage or excessive wear [68],
- **coatings**: nanotribology offers theoretical and experimental support in developing thin films and coatings that reduce friction and wear on surfaces. These coatings are used in various industries, including aerospace, automotive, and electronics [69], [70],
- **nanocomposites** [71], [72].

Nanocomposites are materials that incorporate nanoscale fillers into a matrix material to enhance its properties. These fillers, which can be nanoparticles, nanofibers, nanotubes or nanoclays, are typically dispersed within polymers, metals, or ceramics. The addition of nanoscale materials may significantly improve mechanical strength, thermal stability, electrical conductivity, barrier properties, and other characteristics.

Applications of nanocomposites can be found in the following industries and field of activities.

Automotive industry. Nanocomposites are used to create lightweight and durable automotive parts, reducing the overall weight of vehicles, which improves fuel efficiency and reduces emissions. Adding nanomaterials like carbon nanotubes or nanoclays can improve the mechanical strength and impact resistance of automotive plastics and rubber components.

Aerospace. Nanocomposites are used in the aerospace industry for components that require high strength-to-weight ratios, such as fuselage panels, wings, and structural supports. Nanocomposites with enhanced thermal stability are employed in high-temperature environments, such as engine components and heat shields.

Electronics. Nanocomposites with conductive fillers (e.g., carbon nanotubes or graphene) are used in flexible electronics, sensors, and electromagnetic interference (EMI) shielding materials. In electronic components, nanocomposites can improve dielectric properties, allowing for more compact and efficient devices.

Biomedical applications. These nanomaterials are used in controlled drug delivery systems, where nanoparticles within a polymer matrix can release drugs in a targeted and sustained manner. Nanocomposite scaffolds are used in tissue engineering to provide a structural framework that mimics the extracellular matrix, promoting cell growth and tissue regeneration.

Packaging. Nanocomposites are used in food packaging to enhance barrier properties against gases, moisture and UV radiation, thereby extending the shelf life of products. Incorporating nanoparticles with antimicrobial properties, such as silver or zinc oxide, into packaging materials helps prevent bacterial growth and contamination.

Construction. Nanocomposites in cement and concrete enhance mechanical properties, such as compressive strength and durability, and can also impart self-cleaning or self-healing properties.

Coatings. Nanocomposite coatings provide improved wear resistance, UV protection, and hydrophobic properties for building materials.

The manufacturing and the use of nanocomposites have issues that have not been yet solved, partially or entirely, by scientists. Among these there are the following.

- Dispersion of nanofillers: achieving uniform dispersion of nanoparticles within the matrix is critical for realizing the full potential of nanocomposites. Poor dispersion can lead to agglomeration, reducing the effectiveness of the nanofillers and compromising the material's properties. The solutions offered by today's science are advanced processing techniques such as high shear mixing, ultrasonication, and surface functionalization of nanoparticles are used to improve dispersion.
- Interfacial bonding: the interface between the nanofillers and the matrix plays a crucial role in determining the overall properties of the nanocomposite. Weak interfacial bonding can result in poor load transfer and reduced mechanical performance. Here are two of the solutions for improving the interfacial bonding: surface modification of nanofillers or the use of coupling agents can enhance interfacial bonding, leading to improved mechanical properties.
- Scalability and cost: while nanocomposites offer superior properties, the cost of raw materials and the complexity of processing can limit their large-scale production and commercial viability. Research is ongoing to develop cost-effective production methods and to use more affordable nanomaterials to make nanocomposites more commercially attractive.
- Health and environmental concerns: the potential health risks associated with the production, use, and disposal of nanocomposites, particularly those involving nanoparticles, are not fully understood. There is concern about the release of nanoparticles into the environment and their impact on health. Strict regulatory guidelines and comprehensive risk assessments are needed to ensure the safe handling and use of nanocomposites. Developing biodegradable nanocomposites is also a focus of research.

Examples of nanocomposites include

- carbon nanotube-reinforced polymers: these nanocomposites incorporate carbon nanotubes (CNTs) into a polymer matrix, such as epoxy or polyethylene. The resulting material has significantly improved tensile strength, electrical conductivity, and thermal stability, making it suitable for aerospace and electronics applications.
- graphene oxide nanocomposites: graphene oxide (GO) is used as a filler in various polymer matrices to enhance mechanical properties, thermal conductivity, and barrier properties. These nanocomposites are used in packaging, electronics, and coatings.
- clay-polymer nanocomposites: nanoclay particles are dispersed in a polymer matrix to improve mechanical strength, thermal resistance, and barrier properties. These are commonly used in automotive parts, packaging, and construction materials.

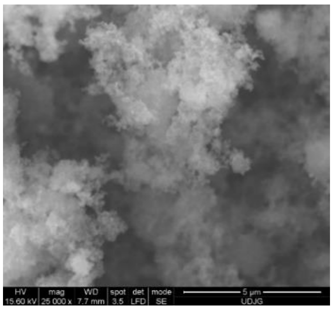
- metal-matrix nanocomposites (MMNCs): these composites incorporate nanoscale ceramic particles, such as silicon carbide (SiC) or aluminum oxide (Al_2O_3), into a metal matrix. The result is a material with enhanced hardness, wear resistance, and thermal stability, used in automotive and aerospace components.
- nanocomposite coatings: nanocomposites are used in coatings to impart properties like scratch resistance, anti-corrosion, and self-cleaning abilities. For example, silica or titania nanoparticles in a polymer matrix can create durable coatings for industrial and consumer products.

Nanocomposites represent a rapidly growing family of nanomaterials, with wide-ranging applications in many industries. Despite the challenges related to dispersion, interfacial bonding, scalability, and health concerns, continued research and development are likely to expand their use even further, leading to new innovations and improved materials.

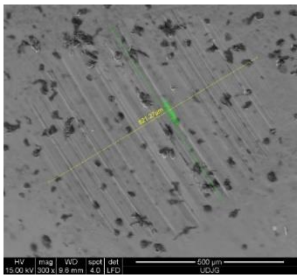
5. Case studies in the favour of multi-scale investigation

In mechanical engineering, the crossing from nano to micro is very probable, for instance, in tribological applications, this occurs due to the dynamics of several factors (sliding, impact, wear etc.). This idea of balancing between nano and micro aspects in tribology is discussed in [73] that explores the interplay between different scales in tribology, particularly how phenomena at the nanoscale can influence or evolve into microscale processes under different mechanical conditions. Also, Bhusan B. [74] associates these two aspects in tribology, nano and micro and provides in-depth coverage of how tribological mechanisms transition across scales, with specific chapters addressing the impact of sliding and wear in micro and nano contexts. These books are good references for understanding these scale-dependent phenomena in mechanical engineering and tribology.

Figure 4 presents a wear scar obtained on a ball from a four-ball test with F=200 N, n=1800 rpm (v=0.69 m/s), after 1 hour of lubricated sliding, using rapeseed oil with 1% wt nanoparticles of TiO_2 as additive [75]. The ball was dried in calm air after being extracted from the lubricant bath. This SEM investigation allows for explaining how the nano additive acted during sliding. It is obvious that this anti-wear and friction additive does not form a continuous film on the sliding contact, but particles of varied sizes remained trapped in the surface texture, becoming an intermediate in supporting load. Even if the powder of TiO_2 has nanoparticles, as given in the supplier catalog [76], after being tested, on the ball there are visible different size of white particles, agglomerated during sliding in larger particles than the initial ones, the smallest being of tens or hundreds of nanometers, but also there were observed particles of several to tens of microns.

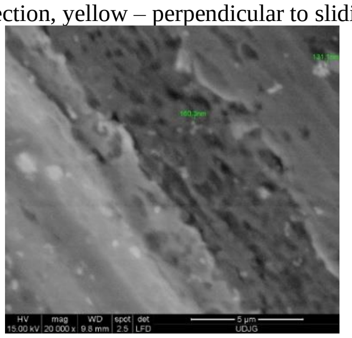


a) Nanoparticles of TiO_2, before being added in rapeseed oil



b) The entire wear scar, green – sliding direction, yellow – perpendicular to sliding

c) Micro scale



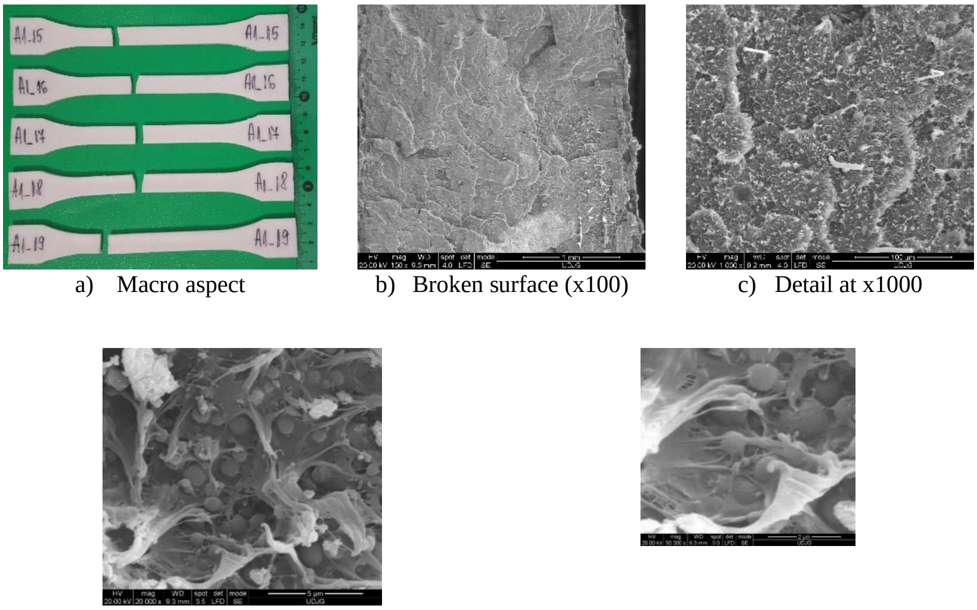
d) Nanoscale

Fig. 4. Multiscale investigation of a wear scar on a ball tested F=200 N, n=1800 rpm (v=0.69 m/s), after 1 hour [75]

The conclusion is that a single scale investigation could not revealed the nanoadditive behavior in sliding contact and this multi-scale investigation could prove that, starting from a nanoadditive lubricant, in contact, these particles agglomerate but they keep protecting the ball surfaces, acting like buffers and micro ball bearing with rolling between big solid bodies, reducing friction. The same process of agglomerating nanoparticles of additive in vegetal oil was noticed in [77], for carbon nanoadditives (graphite, graphene and black carbon) and [78] for nanoparticles of h-BN.

Figure 5 is another argument in favor of studying both nano and micro aspects, especially in polymeric materials. It presents a polymeric blend at different scales in order to explain how the blend components behave under traction: a) a macro image reveals the repeatability of the test (fractures have similar aspect, the strain of the samples are in a narrow range, for values of mechanical characteristics, see [79].

The material is a blend of the following constituents (mass participation): polyamide 6 (PA6) – 20%, polypropylene (PP) – 65%, LDPE – 5%, $CaCO_3$ – 7%, Polybond 3200 – 3%. The detaching of matrix material from the drops of polyamide is extremely specific, the coupling agents (LDPE and Polybond 3200) favoring the adherence of the matrix to the PA6 drops. Also, the matrix under traction forms elongated fibers increases the resistance of the material.



a) Macro aspect b) Broken surface (x100) c) Detail at x1000

d) Detail at x10000 e) Detail at nanolevel

Fig. 5. SEM images of broken surface for a sample made of the polymeric blend PA6+PP+LDPE+$CaCO_3$+Polybond 3200, tested in traction, at 10 mm/min

6. Law issue related to nanomaterials and nanotechnologies

The development and use of nanomaterials and nanotechnologies raises several legal issues, primarily due to their unique properties and the uncertainties surrounding their impact on health, safety, and the environment. These legal challenges span various areas, including regulation, intellectual property, liability, and ethical considerations. A synthetic representation of law issues concerning nanomaterials and nanotechnology is given in Figure 6 and the issues are discussed as follows.

Regulation and standardization

There is a lack of specific regulations as nanomaterials often do not fit neatly into existing regulatory frameworks, which were developed with and for conventional materials in mind. This leads to gaps in regulation where nanomaterials might be inadequately assessed or monitored.

Current regulations may not account for the unique properties of nanomaterials, such as their increased reactivity and potential for greater environmental or biological impact. The European Union's REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals [80]) regulation has been extended to include nanomaterials, but there is still debate about whether it fully addresses the specific risks posed by these materials.

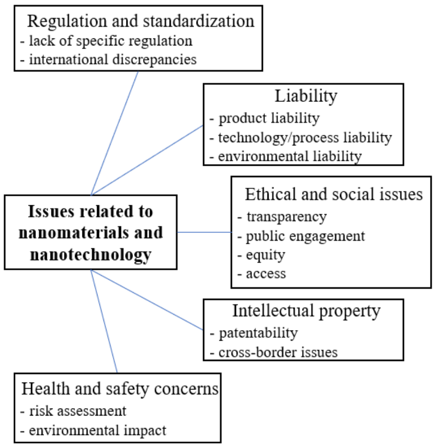


Fig. 6. A synthetic analysis of issues related to nanomaterials and nanotechnology.

Also, if existing, the regulations have discrepancies from one country to another and, in the case of the European Union, these should be harmonized or recognized by all member states, a process that could be longer. Different countries have different approaches to regulating nanomaterials, which can create challenges for companies operating globally. Variability in regulation can lead to difficulties in compliance and trade, as well as "regulatory arbitrage" where companies might seek to operate in jurisdictions with less stringent controls. For instance, the U.S. Environmental Protection Agency (EPA) [https://www.epa.gov/] [81] and the European Chemicals Agency (ECHA) [82] have differing requirements for the testing and registration of nanomaterials, potentially complicating international business operations.

Health and safety concerns

The unique characteristics of nanomaterials, such as their small size and large surface area, can lead to unknown health risks, particularly related to inhalation, ingestion, or skin absorption [83]. For these cases, the risk assessment involves developing innovative screening processes, very experienced specialists and, of course, time and money. There is often insufficient data on the long-term health effects of exposure to nanomaterials, making it difficult to establish clear safety guidelines. Workers in industries that manufacture or use nanomaterials may be at risk of exposure, but there are few established occupational exposure limits for nanomaterials. Nanomaterials might behave differently in the environment compared to bulk materials, potentially leading to unforeseen ecological impacts. Current environmental laws may not adequately address the release of nanomaterials into the environment, leading to potential contamination of water, soil and air. The disposal of products containing nanomaterials is not always regulated differently from conventional materials, even though nanomaterials could pose greater risks to ecosystems.

Intellectual Property (IP)

Nanotechnologies often involve highly specialized and novel inventions, leading to questions about what can be patented and how broad patent claims should be. Overly broad patents might stifle innovation by giving patent holders extensive control over basic nanotechnologies, while narrow patents might not provide sufficient protection. Patents on fundamental nanomaterials, such as carbon nanotubes or graphene, have led to disputes over the scope of patent claims and the potential for "patent thickets" that complicate further innovation.

The global nature of nanotechnology research and development raises issues related to the enforcement of intellectual property rights across different jurisdictions. Inconsistent patent laws and enforcement mechanisms can lead to difficulties in protecting and commercializing nanotechnologies internationally. A company might patent nanotechnology in one country but find it difficult to enforce that patent in another country with weaker patent protections.

Liability

Manufacturers of products containing nanomaterials could face liability if those products cause harm to consumers, especially if the risks were not adequately disclosed. Deciding liability can be complicated cause of lack of consensus on the risks associated with nanomaterials and by difficulties in proving causation. If a product containing nanoparticles is found to cause health problems, the manufacturer could be liable for damages, but only if the harm can be linked to the nanoparticles.

Companies might be held liable for environmental contamination caused by the release of nanomaterials, even if the potential for harm was not known at the time of release. Environmental laws like the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) [84] in the USA could impose liability for cleanup costs, even if the nanomaterials were used in compliance with existing regulations. A company that manufactures nanomaterials might be required to pay for the cleanup of a contaminated site, even if the contamination occurred inadvertently and was not anticipated under current regulations.

Ethical and Social Issues

There is ongoing debate about how much information about nanomaterials should be disclosed to the public, particularly on potential risks. But considering the diversity of education levels, professions and specializations, the explanations could be irrelevant or ununderstood to non-specialists. The university introduced chapters in their curricula that include nanomaterials and nanotechnologies, predominantly in engineering, agriculture, medicine and forensic disciplines.

Balancing the need for public transparency with the protection of proprietary information is difficult, especially in industries where nanotechnology is a key competitive advantage. Consumers may demand labeling of products containing nanomaterials, but manufacturers may be reluctant to disclose such information if it reveals trade secrets.

Among the few works on ethics in nanotechnology [85], [86], the book "Environmental, Ethical, and Economical Issues of Nanotechnology" [83] includes two chapters about "Ethical Issues in Nanotechnology" [87], [88]. Maurício

Machado da Rosa wrote that, in the absence of clear regulation and lack of information and understanding for the public, the ethics in nanotechnology are difficult to identify and formulate. It is a significant difference between acceptance of science novelty by the public and obeying ethics in research and for products and fabrication. The use of nanotechnology could improve life in a society enough developed to access the nanoscale in products and fabrication, but this could enlarge the gap between these and less developed countries. Is it ethical? The answer is much more complex than "yes" or "no". Society needs to progress, even if this progress is more intense in developed countries. Introducing beneficial nanotechnologies requires an educational elite that could be formed in universities with facilities where to study nanosciences. And this could be a vicious circle. A list of ethical issues established now could be obsolete only several months in the future. The author proposes the analysis case-by-case, but this is time consuming, and it could be outside or on the edge of the existing regulation frame. The main ethical principles guiding the acceptance of nanoresearch, nanoproducts and nanotechnologies are "beneficence, non-malfeasance, justice and autonomy" [87]. We found it interesting to notice the responsibility of government in regulating risk identification and assessment. We, the authors of this paper, consider that one of the government's responsibilities is to support educational and research investment in order to have specialists that could teach, innovate and produce in such arrowhead field – nanotechnology.

The benefits of nanotechnology might not be evenly distributed, potentially worsening existing social inequalities. Ensuring that developing countries and marginalized populations have access to the benefits of nanotechnology, while also protecting them from potential risks, is a significant ethical challenge. High costs associated with the development and implementation of nanotechnology could limit its availability to wealthier nations, leaving poorer countries behind.

In Europe, a prominent legal issue involving nanomaterials has centered around the regulation and use of titanium dioxide (TiO_2) nanoparticles in consumer products, particularly in food and cosmetics. This nanomaterial is also used in lubricants for reducing friction and wear and in paintings for inducing glowing white color. Titanium dioxide is widely used as a white pigment and opacifying agent in various products, including paints, sunscreens and food products (where it is labeled as E171). The nanoparticles of TiO2 are particularly effective in providing UV protection in sunscreens and enhancing the brightness and opacity of foods and cosmetics. However, concerns have risen about the safety of TiO_2 nanoparticles, especially their potential to cause harm when inhaled or ingested.

In October 2021, the European Commission decided to ban the use of titanium dioxide (E171) as a food additive after the European Food Safety Authority (EFSA) concluded that it could no longer be considered safe [89].

This decision was based on studies suggesting that TiO_2 nanoparticles might have genotoxic effects (i.e., they could damage DNA and potentially lead to cancer). The ban was fully implemented across the European Union (EU) in 2022, making it illegal to sell food products containing TiO_2.

The classification of titanium dioxide as a possible human carcinogen by inhalation (Category 2) by the European Chemicals Agency (ECHA) under the Classification, Labeling and Packaging (CLP) Regulation in 2020 sparked significant controversy [90]. Industry groups argued that the classification did not adequately distinguish between the risks posed by bulk TiO_2 and its nanoparticulate form, leading to concerns over the implications for a wide range of industries. Some member states, such as France, took a more precautionary approach by banning the use of TiO_2 in food even before the EU-wide ban, reflecting differing national approaches to the precautionary principle in regulating potentially hazardous substances [France's ban on titanium dioxide] [91].

The reclassification and subsequent bans have had significant implications for industries using TiO_2 nanoparticles. Manufacturers of food, cosmetics and other products containing TiO_2 have had to reformulate their products or seek alternative substances, which has led to legal and economic challenges. Companies have challenged these regulatory decisions in court, arguing that the scientific evidence does not conclusively prove that TiO_2 nanoparticles are harmful when used in the manner prescribed. These legal disputes have raised broader questions about how the EU regulates nanomaterials and the balance between innovation and consumer safety.

The case of titanium dioxide in Europe illustrates the complexities of regulating nanomaterials [92]. The ban on TiO_2 as a food additive represents a significant step in the EU's precautionary approach to chemical safety, particularly concerning nanomaterials where there is scientific uncertainty. It has led to increased scrutiny of other nanomaterials used in consumer products and could set a precedent for more stringent regulation of nanotechnology in the EU [93].

This case underscores the challenges faced by regulators in assessing the safety of nanomaterials, particularly when scientific evidence is still emerging. It also highlights the potential for significant economic and legal repercussions for industries reliant on nanotechnology, as well as the ongoing debate over the proper balance between protecting public health and fostering innovation.

The legal issues surrounding nanomaterials and nanotechnologies are complex and multifaceted, involving questions of regulation, health and safety, intellectual property, liability, and ethics. As the field evolves, legal frameworks will need to adapt to address these challenges, ensuring that nanotechnology develops in a safe, equitable, and beneficial way for society.

7. Conclusions

These differences in terminology reflect the varied focus and applications considered by each organization, and understanding these can be crucial for researchers and professionals working in international and interdisciplinary contexts.

While there is consensus on the fundamental aspect of a nanostructure being a structure with at least one dimension in the nanoscale range (1 nm to 100 nm), different organizations emphasize various aspects of the properties and applications of nanostructures. ISO and IUPAC focus on unique properties, ASTM includes internal and surface structures, and IEEE highlights specific types of novel properties relevant to electrical and electronic applications.

These examples illustrate the diverse applications and forms of nanostructures, highlighting the unique properties and functionalities that arise at the nanoscale as emphasized by different standard-setting organizations.

As concerning mechanical engineering and tribology, we think that the boundary between nano and micro in these fields are easily disturbed as the functioning of the mechanical systems implies variations of input parameters that could develop phenomena and processes that could change/destroy nanostructures and that obliges the researchers to study the system at different scale for understanding and commanding its behavior and especially for designing and maintaining their durability and reliability.

Could Romanian research work in the nano-field?

It is difficult to have an answer in different fields. I will discuss only a few aspects of my team's nano-level studies.

The first condition is to have proper equipment for materials investigation, phenomena and processes at nanolevel. Research at nanolevel implies access to nanomaterials and sophisticated fabrication systems (even at laboratory level) that implies large investments in a multidisciplinary research center.

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