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Regulating Nanotechnology: Ensuring Responsible and Safe Innovation in the Advancement of Science and Technology

Regulación de la nanotecnología: garantizando la innovación responsable y segura en el avance de la ciencia y tecnología

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Resumen

Nanotechnology has significant potential in industries, medicine, and technology, but its rapid development raises concerns about health and environmental risks. Implementing regulations is crucial for responsible and safe use. Costa Rica has adopted policies and strategies, including standardization processes, to promote innovation and sustainable development. However, challenges and opportunities persist in implementing nanotechnology regulations. This article examines key challenges and opportunities, such as corporate culture, training, education, and international cooperation. It concludes that appropriate regulations can create significant opportunities for sustainable industry and economic development. Corporate culture barriers can be addressed through policies promoting social responsibility and sustainability. Training and education are essential for risk awareness and mitigation. International cooperation establishes global standards and prevents fragmented regulation. Implementing suitable nanotechnology regulations in Costa Rica fosters industry responsibility, enhances reputation and competitiveness, and stimulates investment in sustainable technologies. Despite challenges, it is vital to implement regulations for the responsible and safe use of nanotechnology.

Palabras clave: Nanotechnology regulation, soft regulation, hard regulation, Costa Rica regulations, nanotechnology

Abstract

La nanotecnología tiene un gran potencial en industrias, medicina y tecnología, pero su rápido desarrollo plantea preocupaciones sobre riesgos para la salud y el medio ambiente. La implementación de regulaciones es crucial para un uso responsable y seguro. Costa Rica ha adoptado políticas y estrategias, incluyendo procesos de estandarización, para promover la innovación y el desarrollo sostenible. Sin embargo, persisten desafíos y oportunidades en la implementación de regulaciones para la nanotecnología. Este artículo examina los principales desafíos y oportunidades, como la cultura empresarial, la formación, la educación y la cooperación internacional. Concluye que regulaciones adecuadas pueden generar importantes oportunidades para el desarrollo sostenible de la industria y la economía. Las barreras culturales empresariales pueden abordarse a través de políticas que promuevan la responsabilidad social y la sostenibilidad. La formación y educación son esenciales para la conciencia y mitigación de riesgos. La cooperación internacional establece estándares globales y evita una regulación fragmentada. La implementación de regulaciones adecuadas en nanotecnología en Costa Rica fomenta la responsabilidad de la industria, mejora la reputación y competitividad, y estimula la inversión en tecnologías sostenibles. A pesar de los desafíos, es vital implementar regulaciones para el uso responsable y seguro de la nanotecnología.

Keywords: Regulación nanotecnológica, regulaciones blandas, regulaciones duras, regulaciones en Costa Rica, nanotecnología

Introduction

What is nanotechnology?

Nanotechnology involves exploring and manipulating individual atoms and molecules, harnessing their properties on atomic, molecular, and even supramolecular scales for various industrial applications. Initially, nanotechnology was primarily associated with precisely manipulating atoms and molecules to create larger-scale products, a concept referred to as molecular nanotechnology. Later, a broader definition of nanotechnology emerged through the National Nanotechnology Initiative (NNI) efforts from the United States federal government. This definition characterizes nanotechnology as the manipulation of matter possessing at least one dimension within the 1 to 100 nanometers (nm) range, acknowledging the significance of quantum mechanical effects at this quantum-realm magnitude. Consequently, the focus of the definition evolved from a specific technological objective to a comprehensive research category encompassing all forms of research and technologies addressing the unique properties of matter occurring below the specified size threshold.

Nanotechnology and regulations

Nanotechnology is an emerging discipline that has become a field of research and application of great interest worldwide. Its importance is that a material's physical, chemical, and biological properties differ between 1 and 100 nanometers compared to the same material at a larger scale (Bordea et al., 2020; Foladori, 2016). Therefore, its potential to transform various sectors, such as medicine, energy, food, and technology, has generated significant expectations and opportunities for economic and social development. However, it has also raised concerns about its potential risks to human health and the environment (Foladori et al., 2013; Shea, 2005).

In addition, different regulations are used to characterize, measure qualitative properties, and even quantify at the nanoscale, as those followed for particle studies on a micro-scale. This is further increased in the synthesis processes of nanomaterials or their use as raw materials. Likewise, the treatment of waste at the nanoscale and its impact are mandatory points to consider in a regulation process.

In this context, the implementation of soft and hard regulations for nanotechnology has become essential to ensure responsible and safe use. Soft regulations promote responsible and ethical practices in the industry and are applied from the bottom up (Saldívar Tanaka, 2020). In contrast, hard regulations establish mandatory measures and sanctions to ensure compliance with standards and are applied from the top-down (Arnaldi, 2014).

Costa Rica, as a country that has adopted policies and strategies to promote innovation and sustainable development, has begun implementing nanotechnology regulations. However, there are still challenges and opportunities in its implementation. Some challenges include the lack of knowledge and technical capacity, the need to establish clear and agreed-upon standards, and the lack of stakeholder coordination. On the other hand, opportunities include the potential of nanotechnology to drive innovation and sustainable economic growth (Yadav et al., 2021).

This article aims to analyze the challenges and opportunities in implementing soft and hard regulations for nanotechnology in Costa Rica, considering factors such as business culture, training and education, and international cooperation, among others.

What is the importance of regulating nanotechnology?

Regulating nanotechnology is important for several reasons. Firstly, it is essential for private investment and participation in the market and for creating a platform for innovation and commercialization. Secondly, it is imperative to address the risks emerging nanotechnology poses to the environment and human health from a legal and regulatory perspective. So, regulations in nanotechnology are essential for several reasons:

1. **Protection of human health and the environment:** Given that nanoparticles have unique properties that can have unpredictable effects on human health and the environment, it is essential to establish regulations that ensure their safety and minimize their negative impact (Foladori et al., 2013; Lee et al., 2014; Wani & Kothari, 2018; Yang et al., 2019; Zea, 2012).
2. **Responsible research:** Appropriate regulations can promote responsible research and develop-

ment of nanotechnology, maximizing its benefits while minimizing risks. The European Union's Horizon 2020 program is an example of responsible innovation in nanotechnology (Vasen, 2015), aiming to develop governance mechanisms that align with European policies and regulations (Vargas Martínez et al., 2018)

3. **Build consumer trust:** Regulations can help build consumer confidence in the safety and responsible use of nanotechnology products (Foladori et al., 2012). Regulations can build consumer trust by setting clear standards and requirements for developing, manufacturing, and labeling nanotechnology products. These regulations can encompass safety assessments, quality control measures, and guidelines for accurate and transparent product labeling. By enforcing strict safety standards, regulations ensure that nanotechnology products undergo rigorous testing and evaluation to identify and mitigate potential risks. This assures consumers that their products have undergone thorough scrutiny and are safe for use. Also, regulations can require manufacturers to provide clear and accessible information about the presence of nanotechnology in their products. This includes detailed labeling, indicating nanomaterials' use, properties, and associated risks or benefits. Transparent and informative labeling empowers consumers to make informed choices and fosters a sense of trust in the products they purchase (Siegrist & Keller, 2011).
4. **Promote fair trade and competition**: Adequate regulations can ensure that products with nanotechnology meet required safety and quality standards, promoting fair competition and trade.
5. **Prevent unknown risks:** As nanotechnology evolves and new applications are developed, there may be unknown and unforeseen risks. Proper regulations can help prevent these risks (Becker, 2013).
6. **Safety assessment:** This is a critical aspect of nanotechnology regulations as it helps ensure that products are safe for human health and the environment. The safety assessment process may include evaluating the toxicity of nanomaterials, determining their potential for bioaccumulation and persistence in the environment, and assessing the potential risks of exposure to humans and the environment. Regulations may also require companies to submit safety data and information about using nanomaterials in their products. This information can help regulatory agencies evaluate the safety of the products and determine whether they can be approved for commercial use. In addition, regulations may also require ongoing monitoring of products containing nanotechnology to ensure their safety over time. This can include post-market surveillance, regular safety evaluations, and reporting adverse events or incidents (Omlor et al., 2015; Shandilya et al., 2020; Tavernaro et al., 2021).
7. **Risk communication:** Regulations may include requirements for communicating risks associated with nanotechnology products to help consumers make informed decisions and workers take proper precautions (Boholm & Larsson, 2019; Joubert et al., 2020; Giurca, 2022).
8. **International cooperation:** Nanotechnology regulations may be necessary to establish international safety and responsible use standards, ensure practical international cooperation, and avoid misuse of nanotechnology. As nanotechnology knows no boundaries, it is essential to establish global safety and responsible use standards to ensure consistent practices across countries. Collaborative efforts between nations can facilitate the sharing of knowledge, research findings, and best practices in regulating nanotechnology. By promoting international cooperation, countries can work together to address common challenges and concerns related to nanotechnology. This collaboration can lead to harmonized regulatory frameworks prioritizing the safety of human health and the environment while fostering innovation and economic growth. International cooperation in nanotechnology regulation can also prevent nanomaterials' misuse or unethical application. By establishing standard guidelines, countries can discourage using nanotechnology for malicious purposes, such as weaponization or environmental exploitation. International cooperation can enhance the effectiveness of nanotechnology regulations through information sharing, joint research projects, and the exchange of expertise. It enables countries to learn from each other's experiences, leverage collective knowledge, and avoid duplicating efforts. This collaboration is valuable in addressing emerging risks and adapting regulations to keep pace with technological advancements (Ezema et al., 2014; Gao et al., 2016; Wu et al., 2019).

9. **Social Responsibility:** Adequate regulations can help ensure that nanotechnology is used in a socially responsible manner rather than solely benefiting certain companies or groups. The "nano dialogue" is necessary, and democratization rescues the care figure so that the private and public scientific community and industry can avoid extremes and ensure the responsible use of nanotechnology (Campillo Vélez & Zuleta Salas, 2014).
10. **Transparency:** Regulations can ensure transparency in developing and using nanotechnology, which is fundamental for generating trust and allowing informed public dialogue (Husain et al., 2023; Wiechers & Musee, 2010; Zia et al., 2023).
11. **Protect workers:** Regulations can also ensure the safety of workers handling nanotechnology and minimize risks associated with exposure. To ensure worker safety, regulations can establish guidelines for handling and disposing of nanomaterials, including proper labeling, storage, and transportation of materials. Regulations can also require employers to provide appropriate protective equipment, such as respirators and gloves, and monitor workers' health exposed to nanomaterials. Additionally, regulations can mandate training and education for workers on the potential hazards associated with nanomaterials and how to handle them safely (Gomez-Villalba et al., 2023; Murashov & Howard, 2013; Schulte et al., 2014, 2022).
12. **Ethical research and development:** Regulations play a critical role in ensuring that research and development of nanotechnology are conducted ethically and with respect for human rights. Nanotechnology has the potential to revolutionize many aspects of our lives, but it also poses significant ethical challenges, particularly regarding human health and safety. To ensure that research and development of nanotechnology are conducted ethically, regulations may require researchers and developers to obtain informed consent from participants in clinical trials, conduct risk assessments, and implement measures to mitigate any identified risks. Regulations may also require that any potential negative impacts on human rights, such as privacy violations, be identified and addressed. Additionally, regulations may require researchers and developers to consider their work's potential social, economic, and environmental impacts. For example, it may be necessary to consider the potential impact of nanotechnology on vulnerable populations or the environment and to take steps to mitigate any possible adverse effects. (Kim et al., 2012; Campillo Vélez & Zuleta Salas, 2014).
13. **Intellectual property protection:** Regulations can protect the intellectual property of companies and researchers working in nanotechnology, fostering innovation and the development of new products. By implementing robust measures to safeguard intellectual property rights, regulations can provide a conducive environment for companies and researchers to invest in and pursue innovative advancements in nanotechnology. Nanotechnology often involves significant research and development efforts, requiring substantial time, resources, and expertise investments. Intellectual property protection ensures that the companies and researchers involved in nanotechnology have the incentive and confidence to continue their innovative work, knowing that their ideas, inventions, and discoveries will be safeguarded from unauthorized use or exploitation. When companies and researchers have the assurance that their intellectual property rights will be protected, they are more likely to engage in collaborations, share knowledge, and commercialize their innovations. This adopts a culture of innovation and encourages the development of new products and technologies that can transform various industries (Fiedler & Welpe, 2010). Moreover, intellectual property protection incentivizes companies and researchers to disclose their findings and inventions, facilitating the dissemination of knowledge and contributing to the overall advancement of the field. It also promotes fair competition by ensuring that those who invest in research and development efforts are rewarded for their contributions, thus encouraging further innovation and investment in nanotechnology. Regulations incentivize innovation and attract investments in the nanotechnology sector by providing a legal framework for intellectual property protection. Investors are more likely to fund research and development initiatives when they have confidence that intellectual property rights will be respected and upheld (Chen, 2021; Tullis, 2012).
14. **Protect ecosystems:** Adequate regulations can help ensure that nanotechnology does not hurt ecosystems and biodiversity. Adequate regula-

tions can help prevent or minimize these impacts by requiring proper disposal of nanomaterials and monitoring their release into the environment. Additionally, regulations can promote the development of sustainable and environmentally friendly nanotechnologies that minimize harm to ecosystems and promote biodiversity. By ensuring that nanotechnology is developed and used responsibly and sustainably, we can protect our natural resources and promote a healthy environment for current and future generations (Rodríguez-Ibarra et al., 2020).

15. **Corporate responsibility:** Regulations can help promote the corporate responsibility of companies working with nanotechnology, improving their reputation and relationship with consumers. By complying with these regulations, companies can demonstrate their commitment to ethical and responsible behavior, enhancing their reputation and improving their relationship with consumers. Furthermore, responsible practices can help companies avoid costly legal and financial consequences associated with non-compliance, making it a sound business decision to prioritize corporate responsibility using nanotechnology (Berger et al., 2017).
16. **Promote sustainability:** Regulations can promote the sustainability of nanotechnology and ensure its responsible and sustainable use in the long term. Sustainability encompasses the preservation of natural resources, the reduction of environmental impacts, and the promotion of social well-being. Nanotechnology regulations can address these concerns by imposing requirements and guidelines that promote the development and use of nanomaterials and nanotechnology processes that are environmentally friendly, energy-efficient, and resource-efficient. For example, regulations can encourage using green nanomaterials with minimal ecological footprints and promote reducing or eliminating hazardous substances in nanotechnology applications. By encouraging the adoption of sustainable practices, regulations can minimize the potential adverse effects of nanotechnology on the environment and human health. Additionally, nanotechnology regulations can fión, oster social sustainability by addressing potential social and ethical implications. They can promote responsible research and development practices that consider the social impact of nanotechnology, including issues related to worker safety, consumer protection, and equitable access to nanotechnology benefits (Kamarulzaman et al., 2020; Stone et al., 2018).
17. **Protect privacy:** Regulations can ensure that nanotechnology is not misused to collect or process personal information from consumers. As nanotechnology advances, there is a growing concern about its potential to collect and process personal information without individuals' consent or knowledge. Therefore, regulations play a vital role in safeguarding privacy rights and preventing any inappropriate or unauthorized use of nanotechnology for data collection. To address this concern, regulations can establish clear guidelines and limitations on collecting, using, and storing personal information obtained through nanotechnology applications. These regulations can specify the conditions under which consent must be obtained, the purposes for which personal data can be collected, and the security measures that must be implemented to protect individuals' privacy (Corley et al., 2009; Kamarulzaman et al., 2020).
18. **Public education:** Regulations can educate the public about nanotechnology's potential risks and benefits. By requiring companies to provide clear and accessible information about the products and processes involving nanotechnology, regulations can help promote transparency and informed decision-making. Additionally, regulations can support the development of public awareness campaigns and educational programs to increase understanding of the technology, its potential applications, and the measures to ensure its safety. Through public education initiatives, regulations can also help address concerns or misconceptions about nanotechnology in the broader community. By providing accurate information and highlighting the potential benefits of nanotechnology, such as improved medical treatments and more efficient energy production, regulations can help to build trust and confidence in the technology. Overall, public education is an essential component of responsible nanotechnology governance. By promoting greater understanding and awareness of the technology, regulations can help realize nanotechnology's potential benefits while minimizing potential risks to human health and the environment

(Babatunde et al., 2020; Bostrom & Lofstedt, 2010; Kamarulzaman et al., 2020).

19. **Protect animal health:** Nanotechnology in products that may come into contact with animals, such as animal feed or veterinary products, raises concern about potential impacts on animal health and welfare. Adequate regulations can help ensure that these products are safe for animals to consume or use and do not pose any risks to their health. This can be achieved through careful evaluation of the potential risks associated with the use of nanotechnology in these products, as well as monitoring and testing to ensure their safety. By protecting animal health and welfare; these regulations can also promote the responsible use of nanotechnology and improve public confidence in products that contain it (Chandra Mohana et al., 2020; Kuzma, 2010; Rajwade, 2023; Ulucan Karnak et al., 2023).
20. **Prevent pollution:** Nanotechnology, with its unique properties and applications, has the potential to contribute to environmental sustainability by offering innovative solutions to address pollution challenges. Regulations play a crucial role in ensuring that nanotechnology is used to minimize pollution and its adverse environmental effects. By imposing strict guidelines and standards, regulations can promote responsible practices throughout the lifecycle of nanotechnology products, from manufacturing to disposal. One significant area where nanotechnology can contribute to pollution prevention is developing advanced pollution control technologies. Nanomaterials and nanotechnology-based processes can enhance the efficiency of pollution control systems, such as air filters, water treatment systems, and soil remediation methods. By harnessing the unique properties of nanomaterials, these technologies can capture and remove pollutants more effectively, reducing their release into the environment (Bodzek et al., 2020; Iravani, 2021; Yunus et al., 2012).
21. **Protect consumer rights:** Regulations can ensure that consumers have access to accurate and reliable information about products containing nanotechnology and that their privacy and security rights are respected. Regulations can require clear labeling and disclosure of nanotechnology-enabled products, allowing consumers to make informed choices based on their preferences and potential concerns. By providing accurate information about the presence of nanotechnology in products, consumers can better understand the potential benefits and risks associated with their use. Likewise, regulations can establish product safety assessments and testing guidelines to ensure that nanotechnology-enabled products meet the necessary quality and safety standards. This includes evaluating the potential risks of using nanomaterials, such as toxicity or allergenicity and setting limits or restrictions to protect consumers from potential harm (Kuzma & Kuzhabekova, 2011).
22. **Quality assurance:** Regulations can establish quality standards for products containing nanotechnology, improving the quality and safety of the products (Abbott et al., 2012; Laeeque et al., 2006; Marchant et al., 2009)
23. **Monitoring and evaluation:** Regulations can include requirements for continuous monitoring and evaluation of nanotechnology and its products, helping to detect and prevent long-term safety problems (Aljenbaz & Çağnan, 2020; Becker, 2013; Kim et al., 2012; Zuo et al., 2009).

Hard and Soft Regulations

Regulations can be classified into two main categories: soft and hard. Soft regulations are those that are not mandatory and are based on recommendations and guidelines for good practices. These voluntary regulations encourage stakeholder cooperation and commitment (Fredriksson et al., 2012). However, there are occasions when these regulations become mandatory, changing expectations of what constitutes acceptable behavior (Saldívar Tanaka, 2020). On the other hand, hard regulations are mandatory and may be backed by sanctions and fines.

In the case of nanotechnology, soft regulations may include the development of codes of conduct, promoting transparency and open communication about potential risks, and implementing training and education programs. These regulations can help encourage the industry and other stakeholders to adopt responsible practices. Some soft regulations are proposed by institutions that need more authority to create laws that bind nanotechnology or are guidelines issued by regulatory agencies, such as UN agencies, or supranational bodies, such as the OECD and ISO (Abbott, 2012).

On the other hand, hard regulations may include legal requirements for labeling and risk assessment, pre-authorization of products and processes before commercialization, and the imposition of sanctions and fines for non-compliance. These regulations may be necessary to protect consumers and the environment from the potential risks of nanotechnology.

Considering the benefits and potential risks, a balanced and proportionate approach is needed to regulate nanotechnology. It is essential to encourage innovation and development of nanotechnology while ensuring it is used responsibly and safely.

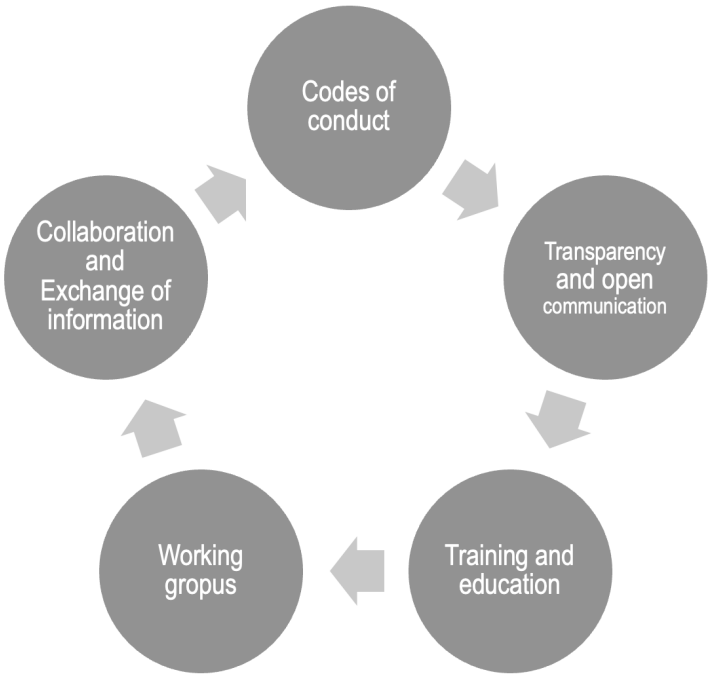
Some possible soft regulations in the context of nanotechnology could include the following (Figure 1):

1. Development of codes of conduct for companies and organizations involved in nanotechnology, establishing ethical and social responsibility standards for developing, producing, and commercializing nanotechnology products and processes.
2. Promotion of transparency and open communication about potential risks associated with nanotechnology by disclosing clear and accessible information about the benefits, risks, and precautionary measures related to nanotechnology products and processes.
3. Development of training and education programs to promote awareness and understanding of nanotechnology's safety, health, and environmental aspects for the industry and the general public.
4. Establishment of interdisciplinary working groups involving experts in science, technology, law, ethics, health, and environment, to monitor and evaluate the development and application of nanotechnology, identify potential risks, and establish preventive and control measures.
5. Encouragement of collaboration and exchange of information among companies, organizations, governments, and other stakeholders involved in nanotechnology, through specialized networks and forums that allow for sharing of knowledge, good practices, and innovative solutions.

It is important to note that these are only some possible soft regulations and may vary depending on

Figure 1

Possible soft regulations in the context of nanotechnology



the country and region. Additionally, these soft regulations are not mandatory and are based on recommendations and guidelines for best practices so that compliance will depend on the willingness and commitment of the actors involved in nanotechnology. Some possible hard regulations in the context of nanotechnology could include the following (Figure 2):

1. Labeling requirement for products containing nanotechnology, including information on ingredients, risks, and precautionary measures for consumers (Akin et al., 2019).
2. Risk assessments for products and processes involving nanotechnology, conducted before commercialization and considering potential risks to health, safety, and the environment.
3. Pre-approvals for nanotechnology products and processes, based on risk assessment and granted by competent authorities.
4. Health and safety standards for workers exposed to nanotechnology, establishing exposure limits, preventive measures, and emergency procedures in cases of exposure.
5. Penalties and fines for non-compliance with nanotechnology regulations may be imposed on companies, organizations, and other actors involved in nanotechnology that do not comply with established standards.

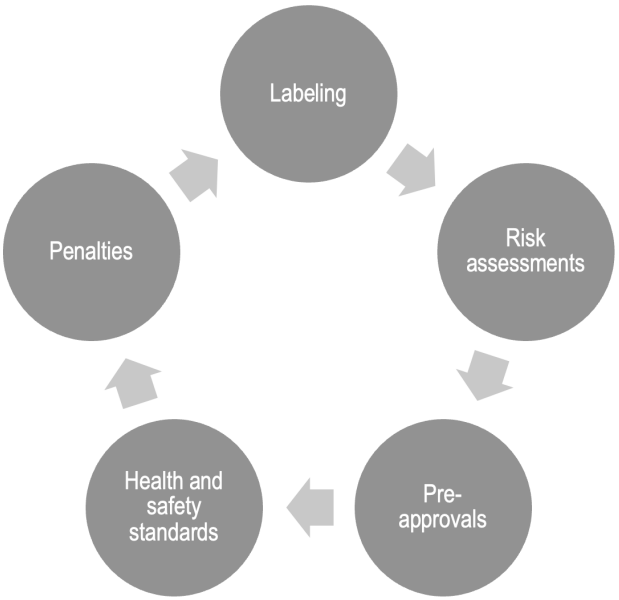
As with soft regulations, it should be considered that these are only some possible hard regulations and may vary depending on the country and region in question.

Some examples of soft regulations in the context of nanotechnology are:

1. **Codes of conduct:** The International Association of Nanotechnology (IANN) has developed a voluntary code of conduct for companies and organizations involved in nanotechnology. This code establishes ethical and social responsibility principles about the development, production, and marketing of products and processes with nanotechnology.
2. **Open communication:** The European Commission has developed a communication strategy on nanotechnology to promote transparency and open communication about the potential risks associated with nanotechnology. This strategy includes disseminating clear and accessible information on the benefits, risks, and precautionary measures related to nanotechnology products and processes.
3. **Training and education programs:** The US National Institute for Occupational Safety and Health (NIOSH) has developed a nanotechnology training program for workers and employers, which aims to promote awareness and under-

Figure 2

Possible hard regulations in the context of nanotechnology



standing of safety, health, and environmental aspects related to nanotechnology.

4. **Interdisciplinary working groups:** The Australian Nanotechnology Expert Group (AEN) is an interdisciplinary group of experts in science, technology, law, ethics, health, and the environment, which monitors and evaluates the development and application of nanotechnology in Australia. The AEN identifies potential risks and establishes preventive and control measures.
5. **Collaboration and information exchange:** The Nanoinnovation Network is a European network for collaboration and knowledge transfer in nanotechnology, which promotes collaboration and information exchange among companies, organizations, governments, and other stakeholders involved in nanotechnology.

Moreover, some examples of hard regulations include:

1. In the European Union, regulations have been implemented for labeling and risk assessment of nanotechnology products (Report on regulatory aspects of nanomaterials, European Parliament, 2008). These regulations require products containing nanotechnology to be explicitly labeled and risk assessments to be performed before commercialization. These hard regulations are necessary to ensure the safety of consumers and the environment of nanotechnology.
2. In the United States, the Occupational Safety and Health Administration (OSHA) has established exposure limits for nanomaterials in the workplace. It has issued guidelines to protect workers' health exposure to nanotechnology (OSHA, 2022). These hard regulations establish mandatory requirements to protect the health and safety of workers and reduce risks associated with exposure to nanomaterials.

Regulation in the field of nanotechnology in México-Brasil-Argentina

It exhibits significant variation across countries. While some countries have implemented specific regulatory frameworks to address the challenges and risks inherent to this discipline, others are developing more comprehensive regulations. Below, I will highlight examples of progress in regulation in some countries in the region:

In Brazil, it has emerged as one of the leaders in nanotechnology regulation in Latin America. In Brazil, ministerial meetings have been held to address the issue of regulating nanotechnologies. In addition, Brazil is one of the Latin American countries that participates in international and national organizations working on the formulation of regulations for nanomaterials, such as the Strategic Approach to International Chemicals Management (SAICM), the Organization for Economic Cooperation and Development (OECD), the International Organization for Standardization (ISO) and others. They are also attentive to regulations presented by Europe and the United States.

Argentina has actively promoted specific legislation in the field of nanotechnology. The National Government of Argentina approved the regulation of the Law for the Promotion of the Development and Production of Modern Biotechnology and Nanotechnology. Law N° 26.270 and its amendment N° 27.685 include nanotechnology within the regulations and are valid until December 31, 20341. The experience of regulating nanotechnologies in Argentina between 2001-2017 is analyzed based on the tracking and processing of legislative projects, institutional initiatives, and expert discourses committed to the co-production of "nano" scientific/legal knowledge.

Mexico also achieved significant advancements in nanotechnology regulation. The Metrology Program for Nanotechnologies (ProMetNano) is a program established by the National Center for Metrology (CENAM) to systematically address the current and foreseeable metrological needs of the country in support of nanosciences and for the use of nanotechnologies. The ProMetNano comprises a cross-functional working group from the four General Directorates of CENAM and currently has 4 scientific coordinators and 6 metrologists who carry out activities related to Nanoscience and Nanotechnologies (NyN). This program is positioned as one of the elements of a continuous and synergistic effort between federal regulatory agencies, industry, and the national scientific community, aimed at taking advantage of nanosciences and nanotechnologies in Mexico, always observing the protection and preservation of the environment and the health of the population.

Ethics-Military and Nanotechnology

Each reason mentioned above is important to ensure nanotechnology's safe and responsible use. No specific reason can be identified as the most important, as all are necessary to ensure that nanotechnology is used responsibly and sustainably. Appropriate regulations should address all safety, health, and environmental concerns while promoting responsible innovation and business competitiveness.

Regarding the military, it is important to note that nanotechnology can have applications in the military field, such as creating lighter and stronger materials and equipment, more precise and efficient sensors, and advanced weaponry systems. However, using nanotechnology in the military can also present risks and security concerns.

Therefore, nanotechnology regulations must also consider its use in the military and ensure that it is used responsibly and sustainably. This may include implementing regulations that address specific risks associated with nanotechnology in the military, such as soldiers' exposure to nanoparticles or the possible use of nanotechnology for biological warfare.

Ethics and nanotechnology in the military are complex issues requiring careful reflection and transparent dialogue (Delgado Ramos, 2022). Developing and using nanotechnology in the military can pose ethical challenges, as it can increase the effectiveness and precision of weaponry systems. Still, they can also increase the risk of injury and death for combatants and civilians.

It is essential to consider the ethical implications of using nanotechnology in the military, such as the responsibility to ensure that it is used responsibly and moderately and the need to protect the human life and dignity of those affected by armed conflict. Advances in nanotechnology can also raise broader ethical questions, such as the scientific community's responsibility in developing technologies that may have negative consequences for society.

Case Costa Rica: challenges and opportunities. INTECO and OECD

In Costa Rica, scientific research in nanotechnology is primarily carried out in state universities and the National Center for High Technology (CeNAT), where the National Laboratory of Nanotechnology (LANOTEC) was created in 2004 under a state, academic, and business initiative. Working with the Costa Rican Institute of Technical Standards (INTECO), which has extensive experience in developing technical standards, a National Technical Committee on Nanotechnology (CTN-060) was established to create the technical basis for a national legal framework on issues related to nanotechnology and select the appropriate basis for the development of Nanometrology in the country. This Technical Committee has been able to work on more than 40 technical standards on the subject of nanotechnology, which include basic concepts, definitions, characterization, manufacturing processes, risk assessment, voluntary labeling guidelines, occupational health and safety practices, safety data sheets, toxicological evaluation, classification, and categorization (INTECO).

A study by Cabello et al. (2020) based on a survey of the business, government, and research sectors of Costa Rica showed the need to create a sustainable regulatory model for nanotechnology that protects consumers and provides specific regulations to different productive sectors due to the possible toxicity and increased exposure to nanomaterials. Hence, efforts are being developed in the country on this topic.

On the other hand, in May 2021, Costa Rica became the 38th member country of the Organization for Economic Cooperation and Development (OECD, 2020), the fourth Latin American country to take this step, concluding the accession process that began in 2015. The country underwent in-depth technical reviews by 22 OECD committees during those years. One of those committees corresponds to Chemicals and the Working Group on Chemicals, Pesticides, and Biotechnology, of which LANOTEC is a part and remains actively working on implementing substantive OECD legal instruments within the committee's competence and Costa Rica's policies and practices in the field of chemicals, (OSHA, 2022).

In addition, the laboratory is part of the Working Party on Manufactured Nanomaterials (WPMN-OECD), where the assessment of hazards and risks of nanomaterials is promoted. The main contribution of this group has been an evaluation to apply the current OECD testing guidelines to the 11 most frequently used nanomaterials. The OECD published the results in 2015.

Likewise, international cooperation is being carried out on human health and environmental safety issues of manufactured nanomaterials and other advanced materials for their respective regulation, considering voluntary, legislative, or other management

schemes. This includes working on the most common types of voluntary nanotechnology surveillance, such as registries, labeling, codes of conduct, risk management systems, technical guides, and standards (Chiancone et al., 2021).

Conclusions

Nanotechnology stands as a captivating and promising scientific realm, poised to reshape our daily lives profoundly. However, alongside its potential benefits, the utilization of nanotechnology carries inherent risks, particularly concerning human health and environmental impact. Thus, establishing judicious regulations is imperative to ensure nanotechnology's secure and ethical application. These regulations safeguard human well-being and our surroundings and serve as catalysts for conscientious innovation, cultivating consumer confidence, and fostering a climate of equitable competition.

Consequently, a collaborative effort among diverse stakeholders, encompassing governmental bodies, entrepreneurs, scientists, and consumers, is essential. An open dialogue must ensue to collectively determine the best strategies for managing and overseeing nanotechnology's multifaceted products, applications, and interests. While several tools are voluntary, the need for more robust and comprehensive measures becomes evident.

Costa Rica, notably, has exhibited commendable strides in both the advancement of nanotechnology and the establishment of regulatory frameworks for its prudent and accountable utilization. The country's inclusion in the OECD has further facilitated international collaboration, enabling active engagement in working groups and committees devoted to nanotechnology and chemical management. Despite these achievements, the journey towards effective implementation of regulations persists, propelling the pursuit of responsible and sustainable innovation in nanotechnology.

Author contributions

José Roberto Vega-Baudrit conceived the idea, the background research, and conceptualization, and Melissa Camacho did the background research, writing draft, and conceptualization. Andrea Araya did the final writing, and Rebeca Corrales-Brenes did the conceptualization and final writing.

Conflicts of interest

We do not have any conflict of interest.

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