Journal of Sustainable Engineering & Green Technologies
ISSN: XXX-XXX Volume – 2, Issue – 1, 2026
DOI:

# NAVIGATING THE ETHICAL AND SUSTAINABLE FRONTIERS OF NANOTECHNOLOGY

**SALAHELDIN ELABIAD[1]**

[1]Department of Pharmaceutical Technology, Girne American University, Mersin 10, Turkey
ORCID ID: https://orcid.org/0009-0009-9076-0233

Salaheldin Elabiad: salahaldinelabiad@gau.edu.tr

**Corresponding Author:** SALAHELDIN ELABIAD

## ABSTRACT

Nanotechnology, with its profound ability to manipulate matter at the nanoscale, is revolutionizing industries such as healthcare, energy, agriculture, and environmental science. This transformative technology offers unprecedented opportunities to address critical global challenges, including disease diagnosis and treatment, renewable energy solutions, and sustainable agricultural practices. However, alongside its remarkable potential, nanotechnology introduces a complex web of ethical dilemmas and sustainability challenges that demand comprehensive exploration.

The rapid development and deployment of nanomaterials raise concerns about their environmental toxicity, long-term health implications, and equitable distribution of benefits. Furthermore, issues surrounding data privacy, surveillance, and societal equity have become increasingly pertinent as nanotechnology intersects with advanced computing and artificial intelligence. Addressing these challenges requires a multidisciplinary approach, integrating robust ethical frameworks, lifecycle assessments, and eco-friendly innovations. Green nanotechnology, which emphasizes the development of sustainable and non-toxic nanomaterials, represents a promising pathway to balance innovation with environmental stewardship.

This review examines the intersection of ethics and sustainability in the field of nanotechnology, focusing on the implications of nanomaterials on human health, ecosystems, and global equity. It highlights the importance of incorporating responsible research and innovation practices to mitigate risks and promote sustainable development. By addressing these critical aspects, this paper seeks to foster a balanced approach that maximizes the benefits of nanotechnology while ensuring ethical integrity and sustainability, thereby contributing to a more equitable and sustainable future for all.

**KEYWORDS:** Nanotechnology, Ethics, Sustainability, Environmental Impact, Green Nanotechnology, Lifecycle Assessment, Nanoethics, Equity in Technology, Risk Management, Responsible Innovation

## INTRODUCTION

Nanotechnology, the manipulation and engineering of materials at the nanoscale (1-100 nanometers), represents one of the most transformative scientific advancements of the 21st century. With applications spanning medicine, electronics, energy, agriculture, and environmental sciences, nanotechnology has unlocked unprecedented opportunities to improve human life and tackle pressing global challenges. Its ability to operate at the atomic and molecular levels allows for innovations in drug delivery systems, efficient energy storage, water purification, advanced coatings, and beyond (Chen et al., 2021; Roco et al., 2011). The versatility and adaptability of nanotechnology promise to revolutionize multiple industries, driving the next wave of technological and economic growth.

Despite its immense potential, nanotechnology brings forth complex ethical dilemmas and sustainability challenges. The unique properties of nanomaterials such as their high reactivity, small size, and novel interactions with biological and environmental systems also contribute to potential risks. For instance, their unknown long-term health effects, environmental persistence, and toxicity present significant challenges to regulators and policymakers. Furthermore, the social implications of nanotechnology, including concerns about privacy, equity, and access, have sparked debates about its responsible development and deployment (Maynard et al., 2011).

The absence of comprehensive ethical guidelines and sustainability frameworks exacerbates these concerns, leaving gaps in policy, regulation, and public understanding. Many stakeholders worry that unregulated or poorly managed nanotechnology could lead to irreversible environmental damage, social inequality, and unintended health consequences (Helland et al., 2008). These concerns underscore the urgent need for a balanced approach to nanotechnology development one that ensures its benefits are maximized while minimizing potential harm.

ISSN: XXX-XXX Volume – 2, Issue – 1, 2026
DOI:

## THE EXPANDING SCOPE OF NANOTECHNOLOGY

Nanotechnology's reach extends into areas as diverse as medicine, where nanoscale drug carriers have improved targeted delivery and reduced side effects, and renewable energy, where nanomaterials are revolutionizing battery technologies and solar panels (Wong & Liu, 2019). Similarly, the agriculture sector benefits from nano-enabled fertilizers and pesticides that increase efficiency while minimizing environmental impact. These advances highlight the dual-edged nature of nanotechnology: while it offers solutions to pressing global problems, it simultaneously introduces risks that require thorough evaluation and mitigation.

## ETHICAL IMPLICATIONS: A GROWING CONCERN

Ethical concerns in nanotechnology often center on the implications of its applications for privacy, security, health, and societal equity. For example, the deployment of nanosensors in surveillance systems raises unprecedented privacy issues, as such devices can operate invisibly and unobtrusively. Similarly, unequal access to nanotechnology-enhanced healthcare could exacerbate global inequalities, leaving marginalized populations further behind in terms of medical advancements (Allhoff et al., 2007). Moreover, ethical questions arise regarding the potential misuse of nanotechnology in areas such as bioterrorism, where nanoengineered materials could be weaponized.

## SUSTAINABILITY AS A CORE PRINCIPLE

Sustainability in nanotechnology involves ensuring that its development does not compromise the ability of future generations to meet their needs. This principle is particularly pertinent given the environmental and resource-intensive nature of nanomaterial production. The extraction of rare earth elements, the energy demands of nanoscale manufacturing, and the potential for nanoparticle pollution highlight the urgency of developing green nanotechnological practices (Hischier & Walser, 2012). Sustainable nanotechnology also necessitates the incorporation of lifecycle assessments (LCA) to evaluate the environmental impacts of nanoproducts from cradle to grave.

For example, studies have shown that some nanomaterials, such as carbon nanotubes and titanium dioxide nanoparticles, exhibit significant environmental persistence and toxicity, raising concerns about their disposal and long-term ecological effects (Klaine et al., 2008). Addressing these challenges requires collaborative efforts among researchers, industries, and governments to promote the development of eco-friendly and biodegradable nanomaterials.

## THE PATH FORWARD

This paper argues that the intersection of ethics and sustainability must form the foundation of nanotechnology's growth. By examining these aspects through a multidisciplinary lens, we aim to provide actionable insights and frameworks for responsible innovation in the field. This review will explore the ethical dilemmas and sustainability challenges associated with nanotechnology, emphasizing the importance of integrating ethical considerations and sustainability principles into its research, development, and application. Only by addressing these concerns can the field move towards a more equitable and environmentally responsible future.
Ethical Considerations in Nanotechnology

## HEALTH AND SAFETY RISKS

Nanotechnology presents significant health and safety concerns due to the unique properties of nanoscale materials. Nanoparticles, with their small size and high surface area, can interact with biological systems in ways that larger particles cannot. This has raised alarms about potential toxicological effects. For example, inhalation of carbon nanotubes has been shown to mimic the pathogenicity of asbestos, causing lung fibrosis and other respiratory issues (Donaldson et al., 2006). Furthermore, nanoparticles such as titanium dioxide, commonly used in sunscreens, can penetrate the skin under certain conditions and potentially cause oxidative stress in cells (Jiang et al., 2009).

Occupational exposure to engineered nanomaterials (ENMs) is another critical issue. Workers involved in the production and handling of ENMs may face chronic exposure, leading to unknown long-term health risks. Ethical concerns arise when industries fail to implement adequate protective measures or inform their employees about these risks. This underscores the importance of robust occupational health policies and stringent regulatory oversight (Maynard & Kuempel, 2005).

The implications extend to consumers as well. Products containing nanomaterials, ranging from cosmetics to food additives, are widely available, often without clear labeling. This lack of transparency denies consumers the ability to make informed choices, raising ethical questions about consent and accountability (Schulte et al., 2008).

Journal of Sustainable Engineering & Green Technologies
ISSN: XXX-XXX Volume – 2, Issue – 1, 2026
DOI:

## ENVIRONMENTAL IMPACTS

Nanotechnology's potential environmental impacts are profound and multifaceted. The release of nanoparticles into air, water, and soil during manufacturing, usage, or disposal poses significant risks to ecosystems. For instance, silver nanoparticles, valued for their antimicrobial properties, have been found to disrupt microbial communities essential for ecological balance (Colman et al., 2013). Similarly, carbon-based nanomaterials can accumulate in aquatic organisms, affecting reproduction and growth rates (Handy et al., 2008).

Another pressing concern is the persistence of nanomaterials in the environment. Due to their stability and resistance to degradation, nanoparticles can accumulate over time, leading to unforeseen ecological consequences. The ethical issue here revolves around the precautionary principle: should the development of nanotechnology proceed without fully understanding its environmental impacts? This principle calls for comprehensive environmental impact assessments and the adoption of eco-friendly design principles (Klaine et al., 2008).

Moreover, waste management practices for nanomaterials remain underdeveloped. Improper disposal of nanowaste, such as used nanosensors or coatings, can lead to contamination of landfills and water bodies. Ethical considerations demand that industries and governments prioritize the development of sustainable waste management strategies to mitigate these risks (Hischier & Walser, 2012).

## PRIVACY AND SURVEILLANCE

The miniaturization enabled by nanotechnology has revolutionized surveillance technologies. Nanosensors and nano-enabled cameras can be deployed in inconspicuous ways, enabling unprecedented monitoring capabilities. While this has clear applications in security and law enforcement, it also raises significant privacy concerns. For instance, nanosensors could potentially track individuals' movements or collect personal data without their knowledge or consent (Allhoff et al., 2007).

The ethical dilemma lies in balancing the benefits of enhanced surveillance with the rights to privacy and autonomy. Unregulated use of nano-surveillance technologies could lead to misuse by governments or private entities, resulting in violations of civil liberties. Ethical frameworks must address these risks, advocating for transparent policies, accountability mechanisms, and public dialogue to ensure that nanotechnology serves the public good (Lin & Allhoff, 2008).

## EQUITY AND ACCESS

Nanotechnology holds the promise of addressing global challenges, from eradicating diseases to providing clean energy. However, its benefits are not distributed equitably. High research and development costs, coupled with intellectual property protections, often limit access to nano-enabled solutions in low-income regions. For example, nanomedicine, which offers targeted drug delivery systems, remains prohibitively expensive for many healthcare systems in developing countries (Ebbesen & Kettler, 2006).

This disparity raises ethical questions about fairness and justice. Should life-saving technologies be accessible only to those who can afford them? Addressing this issue requires global collaboration to promote technology transfer, subsidize costs, and ensure that nanotechnology benefits all of humanity (Roco et al., 2011). Additionally, empowering local researchers in developing countries to participate in nanotechnology innovation can bridge the gap, fostering more inclusive development.

Another aspect of equity pertains to the representation of diverse perspectives in nanotechnology governance. Marginalized communities often lack a voice in decisions that affect them, such as the siting of nanotechnology manufacturing facilities or the allocation of research funding. Ethical frameworks should prioritize inclusivity, ensuring that all stakeholders have a seat at the table (Stilgoe et al., 2013).

## ENVIRONMENTAL IMPLICATIONS OF NANOTECHNOLOGY

## ENVIRONMENTAL IMPACT

**Nanotechnology offers transformative benefits across various industries, yet its environmental** implications remain a significant concern. Nanoparticles, due to their unique properties and size, interact differently with biological systems and ecosystems compared to their bulk counterparts. These interactions may lead to unanticipated toxicity, bioaccumulation, and disruption of natural processes. The potential for nanoparticles to persist in the environment and affect diverse ecosystems necessitates a thorough examination of their behavior and impact (Oberdörster et al., 2005; Kah et al., 2013).

Journal of Sustainable Engineering & Green Technologies
ISSN: XXX-XXX Volume – 2, Issue – 1, 2026
DOI:

## PERSISTENCE IN ECOSYSTEMS

Nanoparticles often exhibit high stability and resistance to natural degradation processes, allowing them to persist in ecosystems for prolonged periods. For instance, metal nanoparticles such as silver and titanium dioxide, frequently used in consumer products, can remain in soil and water environments, interacting with microorganisms and aquatic species. These particles may alter microbial communities, impacting the ecological balance and nutrient cycling processes. Such disruptions may lead to cascading effects throughout the food chain (Klaine et al., 2008; Bundschuh et al., 2018).

## BIOACCUMULATION AND BIOMAGNIFICATION

A critical concern with nanoparticles is their potential to bioaccumulate in living organisms and biomagnify across trophic levels. Studies have shown that certain nanomaterials, such as carbon-based nanoparticles and heavy metal oxides, accumulate in fish, algae, and plants. This bioaccumulation not only affects individual organisms but also poses risks to predators higher up in the food chain, including humans. The long-term health implications of consuming organisms contaminated with nanoparticles are not yet fully understood, warranting further research into their ecological and biological impacts (Handy et al., 2011; Hou et al., 2018).

## TRANSFORMATION AND MOBILITY

Nanoparticles in the environment do not remain static; they undergo transformations that can modify their properties and behavior. Environmental factors such as pH, temperature, and the presence of organic matter can lead to changes in particle size, aggregation, or dissolution. For example, studies have shown that silver nanoparticles can dissolve to release toxic silver ions, while carbon nanotubes may aggregate to form larger particles, reducing their mobility but potentially increasing their toxicity. Understanding these transformations is crucial for predicting their long-term environmental fate and impacts (Nowack et al., 2012; Wiesner et al., 2006).

## STRATEGIES FOR MITIGATION

To address these environmental concerns, researchers and industries are exploring green nanotechnology practices. Developing biodegradable nanomaterials that break down into non-toxic byproducts can significantly reduce environmental risks. Additionally, implementing lifecycle assessments (LCAs) can help identify the stages of production, use, and disposal that have the greatest environmental impact. Policies promoting the safe design of nanomaterials, coupled with advanced waste management systems, are also essential to mitigate risks. Collaborative efforts between regulatory agencies, scientists, and industries will play a key role in ensuring that the environmental benefits of nanotechnology outweigh its risks (Anastas & Warner, 1998; Hischier & Walser, 2012).

## NANOMATERIALS AND ECOSYSTEM TOXICITY

One of the primary concerns regarding nanotechnology is the potential toxicity of engineered nanomaterials. Nanoparticles, such as titanium dioxide (TiO2) and silver nanoparticles (AgNPs), are widely used in consumer products ranging from cosmetics to antimicrobial coatings. While these materials provide significant benefits, their release into the environment during production, use, or disposal can harm aquatic and terrestrial ecosystems. Studies have shown that nanoparticles can penetrate cell membranes in aquatic organisms, causing oxidative stress, inflammation, and even mortality. For instance, TiO2 nanoparticles have been found to impair photosynthesis in algae, a critical component of aquatic food chains, disrupting ecological balance (Handy et al., 2008; Bundschuh et al., 2018).

Moreover, the bioaccumulation of nanoparticles in higher organisms, including fish and mammals, raises concerns about long-term ecological impacts and trophic transfer. Research on AgNPs has demonstrated their ability to accumulate in fish tissues, leading to adverse effects on reproduction and behavior. These findings underscore the importance of regulating nanoparticle emissions and developing safer alternatives (Batley et al., 2013; Hou et al., 2018).

## ENVIRONMENTAL FATE AND TRANSPORT OF NANOPARTICLES

Understanding the environmental fate and transport of nanoparticles is crucial for assessing their ecological risks. Nanoparticles exhibit unique behaviors in soil, water, and air, influenced by factors such as particle size, shape, surface charge, and environmental conditions. For example, in aquatic environments, nanoparticles can aggregate or interact with natural organic matter, altering their mobility and bioavailability. Studies indicate that nanoparticles released into wastewater can accumulate in sludge, which is often used as agricultural fertilizer, potentially contaminating soil and crops (Gottschalk et al., 2013; Kiser et al., 2009).

ISSN: XXX-XXX Volume – 2, Issue – 1, 2026
DOI:

In the atmosphere, engineered nanomaterials can serve as nuclei for condensation, contributing to air pollution and affecting climate patterns. Their small size allows them to penetrate deeply into the respiratory system, posing health risks to humans and wildlife. Addressing these issues requires comprehensive lifecycle assessments to track the pathways and transformations of nanoparticles from production to disposal (Nowack et al., 2012; Wiesner et al., 2006).

## STRATEGIES FOR ECO-FRIENDLY NANOTECHNOLOGY

To mitigate the environmental risks associated with nanotechnology, researchers and industries are increasingly focusing on green nanotechnology. This approach emphasizes the development of sustainable nanomaterials and processes that minimize ecological footprints. For example, using biodegradable polymers as nanoparticle carriers can reduce environmental persistence. Similarly, employing plant-based synthesis methods, such as utilizing phytochemicals from leaves and fruits, can replace toxic chemical processes in nanoparticle production (Raveendran et al., 2006; Shankar et al., 2004).

Another promising strategy is the incorporation of lifecycle assessments (LCAs) into the design and manufacturing of nanomaterials. LCAs evaluate the environmental impact of products throughout their lifecycle, enabling the identification of critical stages for intervention. By adopting circular economy principles, such as recycling and reusing nanomaterials, industries can further reduce waste and resource consumption (Anastas & Warner, 1998; Lee et al., 2019).

## ETHICAL CONCERNS IN NANOTECHNOLOGY DEVELOPMENT

Nanotechnology's rapid evolution and vast applications present an array of ethical challenges that demand thorough exploration. Nanoethics, a specialized field dedicated to understanding the moral implications of nanotechnology, seeks to address issues such as equity, safety, privacy, and societal consequences. With the ability to manipulate matter at the molecular level, nanotechnology impacts not only scientific progress but also societal norms and global governance. A nuanced approach to ethics ensures that the development and deployment of nanotechnology benefit humanity while mitigating potential harm (Allhoff et al., 2007; Grunwald, 2012).

## EQUITY AND ACCESSIBILITY

Nanotechnology has the potential to bridge disparities in healthcare, energy, and agriculture, but its uneven distribution could exacerbate global inequities. Historically, technological advancements have often been concentrated in wealthy nations, leaving underprivileged communities with limited access. For instance, nanotechnology-enabled water purification systems and nanomedicines can transform lives in resource-limited settings, yet their high costs and the intellectual property regime surrounding them often restrict accessibility.

To address these challenges, international collaborations and funding mechanisms must be prioritized. Developing open-source nanotechnology platforms and promoting public-private partnerships can also play a vital role in ensuring that benefits are distributed equitably. Policies should aim at capacity building in developing nations, enabling them to harness nanotechnology's potential for socioeconomic progress (Salamanca-Buentello et al., 2005; Invernizzi & Invernizzi, 2007).

In healthcare, nanotechnology offers breakthroughs such as targeted drug delivery systems and early disease detection tools. However, access to these advanced therapies remains limited in low-income countries. Ethical frameworks must advocate for global health equity by encouraging pharmaceutical companies to adopt tiered pricing strategies and ensuring that innovations address pressing public health needs (Mnyusiwalla et al., 2003; Silva & Weissleder, 2016).

## PRIVACY AND SURVEILLANCE CONCERNS

Nanotechnology-enabled sensors and devices are revolutionizing industries but also raising serious privacy concerns. For example, nanosensors used in medical diagnostics or wearable devices collect vast amounts of sensitive personal data. Without stringent data protection laws, this information could be misused by corporations or governments, undermining individual autonomy and trust.

In the realm of surveillance, nanotechnology allows for the development of highly advanced monitoring systems, including nanoscale cameras and tracking devices. While these tools have legitimate applications in security and law enforcement, they also pose risks of overreach and abuse. Ethical considerations must guide the deployment of such technologies to ensure that societal benefits do not come at the cost of fundamental rights. Transparent governance frameworks, coupled with public discourse, are essential to addressing these challenges (Moor, 1985; Gutmann & Thompson, 2008).

TRESEARCH

## DUAL USE DILEMMA

The dual-use nature of nanotechnology, where innovations intended for beneficial purposes can be weaponized, poses a significant ethical challenge. Nanomaterials developed for medicine or energy may be repurposed for military applications, such as the creation of advanced weaponry or stealth technologies. For example, carbon nanotubes, praised for their strength and conductivity, have potential uses in armor or explosives.

The misuse of nanotechnology extends to the development of bioweapons and surveillance systems that compromise national and individual security. To mitigate these risks, global agreements and stringent export controls are necessary. Researchers and policymakers must actively engage in discussions about responsible innovation, considering both intended applications and unintended consequences (Joyner et al., 2012; Miller & Selgelid, 2007).

## FOSTERING RESPONSIBLE INNOVATION

Responsible research and innovation (RRI) provides a framework to address ethical concerns in nanotechnology. RRI emphasizes transparency, inclusivity, and anticipation of societal impacts throughout the research and development process. By involving stakeholders, including scientists, policymakers, and the public, in early discussions, RRI fosters trust and ensures that ethical considerations are integral to technological progress.

Educational initiatives are pivotal in cultivating an ethical culture among researchers. Integrating ethics training into scientific curricula can help future innovators understand the broader implications of their work. Public engagement, through workshops, media, and community dialogues, also plays a critical role in aligning technological advancements with societal values (Stilgoe et al., 2013; Owen et al., 2012).

The ethical dimensions of nanotechnology development underscore the need for a balanced approach that prioritizes both innovation and societal well-being. Addressing issues of equity, privacy, dual-use, and responsible innovation requires a collaborative effort across disciplines and borders. By embedding ethical considerations into the foundation of nanotechnology research and governance, humanity can harness its transformative potential while safeguarding against harm (Rip et al., 2013; Macnaghten et al., 2005).

## SOCIETAL IMPACTS OF NANOTECHNOLOGY

## BRIDGING TECHNOLOGY AND SOCIETY

Nanotechnology, as a transformative field, holds the potential to reshape numerous aspects of modern society, from healthcare and energy to agriculture and communication. However, its integration into daily life raises fundamental questions about its societal impact, including issues of public perception, equitable distribution, and the reshaping of traditional norms. Understanding these societal dimensions is essential for ensuring that nanotechnology serves as a tool for societal advancement rather than division. This section delves into the multifaceted societal implications of nanotechnology, emphasizing the need for inclusive, ethical, and sustainable approaches.

## PUBLIC PERCEPTIONS AND ACCEPTANCE

Public perception plays a crucial role in the societal acceptance of nanotechnology. While the scientific community celebrates the advancements made possible by nanotechnology, the general public often approaches it with skepticism or caution, largely due to a lack of understanding. Studies show that individuals are more likely to accept nanotechnology applications in fields like medicine and environmental remediation but express concern about its use in food and consumer products (Pidgeon et al., 2009; Siegrist et al., 2007).

Misinformation and fear of the unknown further amplify public apprehensions. For instance, media coverage emphasizing the potential risks of nanoparticles, such as toxicity or environmental harm, can overshadow their benefits. Addressing this challenge requires transparent communication strategies that educate the public about the science, benefits, and risks of nanotechnology. Public engagement initiatives, such as community forums and interactive exhibits, can foster trust and encourage informed decision-making (Priest, 2006; Gaskell et al., 2010).

## EQUITABLE ACCESS TO NANOTECHNOLOGY BENEFITS

The transformative potential of nanotechnology often raises concerns about equitable access. While developed nations lead in nanotechnology research and commercialization, developing countries face barriers such as limited funding, infrastructure, and

ISSN: XXX-XXX Volume – 2, Issue – 1, 2026
DOI:

expertise. This disparity risks widening the technological divide, where only a privileged few benefit from innovations, leaving marginalized communities behind.

For example, nanotechnology-based solutions for clean water and energy have the potential to address pressing global challenges. However, the high cost of these technologies often renders them inaccessible to those who need them most. International collaboration and targeted investments are crucial for ensuring that nanotechnology advances serve global rather than regional interests. Policies promoting technology transfer, capacity building, and local innovation can help bridge these gaps and democratize access to nanotechnology (Invernizzi et al., 2008; Salamanca-Buentello et al., 2005).

## RESHAPING TRADITIONAL NORMS AND PROFESSIONS

Nanotechnology's interdisciplinary nature challenges traditional norms, both socially and professionally. In healthcare, for instance, nanomedicine is redefining patient care by enabling personalized treatments and advanced diagnostics. This shift requires healthcare professionals to acquire new skills and adapt to a more technology-driven approach. Similarly, in manufacturing and agriculture, nanotechnology is replacing conventional practices with innovative solutions, such as nanosensors and smart materials (Roco et al., 2011; Silva & Weissleder, 2016).

On a societal level, these changes can disrupt traditional job markets, particularly in industries heavily reliant on manual labor. While nanotechnology creates new opportunities, it may also displace workers without the necessary technical expertise. Educational institutions and governments must collaborate to provide reskilling programs and foster an adaptive workforce capable of thriving in a nanotechnology-enabled future (Shapira et al., 2015; Appelbaum & Parker, 2012).

## ETHICAL IMPLICATIONS FOR SOCIETY

The societal integration of nanotechnology is not without ethical dilemmas. Privacy concerns arise with the development of nanoscale surveillance technologies, which, while beneficial for security, pose risks of misuse. Additionally, the dual-use nature of nanotechnology, where applications intended for civilian use can be weaponized, necessitates careful regulation and oversight (Miller & Selgelid, 2007; Joyner et al., 2012).

Moreover, the societal implications of nanotechnology extend to environmental justice. Communities near manufacturing facilities may face disproportionate exposure to nanoparticle emissions, raising questions about environmental equity. Addressing these issues requires comprehensive ethical frameworks that prioritize fairness, transparency, and accountability in the development and deployment of nanotechnology (Shrader-Frechette, 2002; Macnaghten et al., 2005). Nanotechnology holds immense potential to drive societal progress, but its transformative impact must be managed responsibly to ensure equitable and ethical outcomes. Bridging the gap between scientific innovation and societal needs requires a collaborative approach that includes public engagement, policy development, and international cooperation. By addressing the societal implications of nanotechnology, stakeholders can foster a future where its benefits are accessible to all, aligning technological advancement with the greater good (Rip & Kulve, 2008; Owen et al., 2012).

## HEALTH IMPLICATIONS OF NANOTECHNOLOGY

## A DOUBLE EDGED SWORD

Nanotechnology's potential to revolutionize healthcare is immense, with applications ranging from targeted drug delivery and diagnostic tools to regenerative medicine. However, the same nanoscale properties that make nanomaterials effective in medicine also raise concerns about their health risks. The interactions of nanoparticles with biological systems can result in unintended effects, including toxicity, inflammation, and oxidative stress. Understanding these health implications is crucial for balancing the benefits of nanotechnology with safety considerations (Oberdörster et al., 2005; Fadeel et al., 2012).

## NANOTOXICOLOGY: UNDERSTANDING BIOLOGICAL INTERACTIONS

Nanotoxicology, a field dedicated to studying the potential adverse effects of nanomaterials on biological systems, has highlighted several concerns. Nanoparticles can penetrate cellular membranes, interact with intracellular structures, and generate reactive oxygen species (ROS), leading to oxidative stress. For instance, studies on carbon nanotubes have shown that prolonged exposure can result in pulmonary inflammation and fibrosis, mimicking the effects of asbestos (Donaldson et al., 2006). Similarly, silver nanoparticles, widely used for their antimicrobial properties, have been associated with cytotoxicity in human cells due to their ability to disrupt mitochondrial function (Yang et al., 2012).

Moreover, the biodistribution and persistence of nanoparticles in the body pose significant challenges. Certain nanoparticles, such as quantum dots, have been found to accumulate in organs like the liver and spleen, raising concerns about their long-term effects. These findings underscore the need for thorough preclinical testing and safety evaluations before clinical applications (Chen et al., 2008; Hardman, 2006).

## APPLICATIONS AND SAFETY IN MEDICINE

While nanotechnology offers innovative solutions in medicine, ensuring safety remains paramount. Drug delivery systems using nanoparticles, such as liposomes and polymeric carriers, have improved the efficacy and specificity of treatments. However, the potential for unintended side effects, such as immune reactions or off-target toxicity, necessitates careful design and monitoring. For example, liposomal formulations of chemotherapy drugs like doxorubicin have reduced systemic toxicity but require precise dosing to avoid adverse outcomes (Allen & Cullis, 2013; Torchilin, 2005).

The use of nanomaterials in diagnostic imaging, such as magnetic nanoparticles for MRI, has enhanced the accuracy of disease detection. However, concerns about the biodegradability and clearance of these materials from the body remain unresolved. Researchers are exploring biocompatible and biodegradable alternatives to address these issues, ensuring that nanotechnology advancements do not compromise patient safety (Laurent et al., 2011; Weissleder et al., 2006).

## REGULATORY AND ETHICAL CONSIDERATIONS

The health implications of nanotechnology also raise regulatory and ethical challenges. The lack of standardized testing protocols and classification systems for nanomaterials complicates safety assessments. Regulatory agencies, such as the FDA and EMA, are working to establish guidelines for the evaluation of nanotechnology-based products. These efforts aim to balance innovation with safety, ensuring that new technologies meet rigorous standards before reaching the market (Bawa et al., 2005; Bowman & Hodge, 2007).

Ethically, the integration of nanotechnology in medicine requires transparency and informed consent. Patients must be adequately informed about the potential risks and benefits of nanotechnology-based treatments. Furthermore, addressing disparities in access to nanomedicine is essential to prevent inequalities in healthcare delivery. Collaborative efforts between governments, industries, and academia are crucial for developing policies that prioritize patient safety and equity (Silva & Weissleder, 2016; Mnyusiwalla et al., 2003). Nanotechnology holds immense promise for advancing healthcare, but its health implications must be carefully managed to ensure safe and equitable applications. By investing in nanotoxicology research, developing biocompatible materials, and establishing robust regulatory frameworks, stakeholders can harness the benefits of nanotechnology while minimizing its risks. A proactive approach to addressing health implications will pave the way for responsible and sustainable innovations in nanomedicine (Fadeel et al., 2012; Oberdörster et al., 2005).

## REGULATORY AND POLICY CHALLENGES IN NANOTECHNOLOGY

## THE NEED FOR OVERSIGHT

The rapid growth of nanotechnology has outpaced the establishment of comprehensive regulatory frameworks to govern its development, deployment, and disposal. While nanotechnology promises significant advancements in various fields, its potential risks to human health, the environment, and society underscore the need for robust oversight. Current regulatory systems often struggle to address the unique properties of nanomaterials, such as their size-dependent behavior and interactions with biological systems. This section explores the regulatory and policy challenges in nanotechnology and proposes pathways to address these gaps.

## GAPS IN EXISTING REGULATORY FRAMEWORKS

One of the primary challenges in regulating nanotechnology is the lack of standardized definitions and classification systems for nanomaterials. Regulatory agencies, such as the U.S. Food and Drug Administration (FDA) and the European Medicines Agency (EMA), often rely on existing frameworks for conventional materials, which may not adequately address the unique characteristics of nanoparticles. For example, the high surface-area-to-volume ratio of nanoparticles can lead to enhanced reactivity and toxicity, requiring tailored safety evaluations (Bowman & Hodge, 2007; Maynard et al., 2006).

Another issue is the absence of universal testing protocols for assessing the safety and efficacy of nanomaterials. Toxicological studies on nanoparticles often produce inconsistent results due to variations in particle size, shape, and surface chemistry. These inconsistencies complicate risk assessments and hinder the development of harmonized regulations across regions (Oberdörster et al., 2005; Fadeel et al., 2012).

## CHALLENGES IN MONITORING AND ENFORCEMENT

Even when regulations exist, enforcing them presents significant challenges. The small size and widespread use of nanomaterials make monitoring their production, distribution, and disposal difficult. For instance, nanoparticles can easily enter wastewater systems, evade traditional filtration methods, and accumulate in sludge or aquatic ecosystems. Regulatory agencies often lack the resources and technological tools needed to track these materials effectively (Wiesner et al., 2006; Nowack et al., 2012). Furthermore, the global nature of nanotechnology research and commercialization complicates enforcement. Countries with less stringent regulations may become hubs for the production of potentially hazardous nanomaterials, undermining global safety standards. International cooperation and agreements are crucial to ensuring that nanotechnology development adheres to ethical and safety guidelines worldwide (Bowman et al., 2011; Kearnes et al., 2009).

## EMERGING APPROACHES TO REGULATION

To address these challenges, regulatory bodies are exploring innovative approaches tailored to the complexities of nanotechnology. Adaptive regulatory frameworks, which allow for periodic updates based on new scientific evidence, are gaining traction. For example, the European Union's REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) program has begun incorporating specific provisions for nanomaterials, requiring manufacturers to provide detailed safety data (European Commission, 2018; Hansen et al., 2011).

In addition, lifecycle assessments (LCAs) and precautionary principles are being integrated into regulatory strategies. LCAs evaluate the environmental and health impacts of nanomaterials from production to disposal, helping policymakers identify critical intervention points. The precautionary principle, which advocates for proactive measures in the absence of complete scientific certainty, ensures that potential risks are managed effectively (Anastas & Warner, 1998; Lee et al., 2019).

## THE ROLE OF STAKEHOLDER ENGAGEMENT

Effective regulation of nanotechnology requires collaboration among diverse stakeholders, including scientists, industry leaders, policymakers, and the public. Public engagement initiatives can help build trust and ensure that regulatory decisions align with societal values. For instance, community forums and citizen panels can provide valuable insights into public concerns and priorities, guiding the development of inclusive and transparent policies (Stilgoe et al., 2013; Macnaghten et al., 2005). Industry participation is equally important. Companies developing nanotechnology-based products must adopt responsible innovation practices, such as adhering to voluntary safety standards and conducting rigorous testing. Partnerships between industry and regulatory agencies can facilitate the exchange of knowledge and resources, promoting compliance and innovation (Owen et al., 2012; Rip et al., 2013).

## TOWARDS A HARMONIZED FRAMEWORK

The regulatory and policy challenges in nanotechnology highlight the need for a harmonized, science-based approach that balances innovation with safety and sustainability. By addressing gaps in existing frameworks, enhancing monitoring capabilities, and fostering stakeholder collaboration, policymakers can ensure that nanotechnology develops responsibly. Proactive and adaptive regulations will not only mitigate risks but also foster public trust and global cooperation, enabling nanotechnology to reach its full potential (Bowman & Hodge, 2007; Kearnes et al., 2006).

## CONCLUSION

Nanotechnology stands at the frontier of scientific innovation, with the potential to transform multiple domains, including healthcare, environmental science, and societal structures. This review has highlighted critical aspects of nanotechnology, focusing on its ethical, societal, health, and environmental implications. While nanotechnology promises significant advancements, it also presents complex challenges that demand a multidisciplinary and proactive approach.

The environmental impact of nanotechnology underscores the importance of adopting green practices and sustainable lifecycle assessments. Similarly, its societal implications call for public engagement, equity in access, and regulatory oversight to ensure that its benefits are universally distributed. The health risks associated with nanomaterials further highlight the need for rigorous safety evaluations and ethical guidelines in their development and application.

To address these challenges, stakeholders including scientists, policymakers, industries, and the public must work collaboratively to establish robust frameworks for responsible innovation. By integrating ethical considerations and sustainability into every stage of nanotechnology development, we can maximize its potential while minimizing its risks.

Nanotechnology is not just a technological revolution; it is a societal endeavor. Its future lies in balancing innovation with responsibility, ensuring that it serves humanity and the environment alike. This journey requires continued research, dialogue, and governance, fostering a future where nanotechnology contributes to a sustainable and equitable world.

## REFERENCES


1. Allhoff, F., Lin, P., & Moore, J. (2007). What is nanotechnology and why does it matter? From science to ethics. Wiley-Blackwell.
2. Allen, T. M., & Cullis, P. R. (2013). Liposomal drug delivery systems: From concept to clinical applications. Advanced Drug Delivery Reviews, 65(1), 36–48. https://doi.org/10.1016/j.addr.2012.09.037
3. Anastas, P. T., & Warner, J. C. (1998). Green chemistry: Theory and practice. Oxford University Press.
4. Appelbaum, R. P., & Parker, R. (2012). Innovation and jobs in the nanotechnology economy: The cases of the U.S. and China. Journal of the Knowledge Economy, 3(4), 286–304. https://doi.org/10.1007/s13132-012-0083-5
5. Batley, G. E., McLaughlin, M. J., & McCall, M. J. (2013). Fate and risks of nanomaterials in aquatic and terrestrial environments and the food chain. Environmental Toxicology and Chemistry, 32(2), 254–261. https://doi.org/10.1002/etc.2042
6. Bawa, R., Johnson, S., & Fischer, G. (2005). Nanotechnology: A new frontier in medical innovation. Drug Discovery Today, 10(23-24), 1605–1611. https://doi.org/10.1016/S1359-6446(05)03613-5
7. Bowman, D. M., & Hodge, G. A. (2007). A small matter of regulation: An international review of nanotechnology regulation. Columbia Science and Technology Law Review, 8, 1–36.
8. Bowman, D. M., Hull, M., & Purkait, P. (2011). Nanotechnology environmental health and safety: Research needs. Woodrow Wilson International Center for Scholars.
9. Bundschuh, M., Filser, J., Lüderwald, S., McKee, M. S., Metreveli, G., Schaumann, G. E., ... & Wagner, S. (2018). Nanoparticles in the environment: Where do we come from, where do we go to? Environmental Sciences Europe, 30(1), 6. https://doi.org/10.1186/s12302-017-0179-z
10. Chen, L., Liu, J., & Zhang, Q. (2021). Nanotechnology in agriculture: Current status, challenges and future opportunities. Science of the Total Environment, 753, 141975. https://doi.org/10.1016/j.scitotenv.2020.141975
11. Chen, Z., Meng, H., Xing, G., Chen, C., Zhao, Y., Jia, G., ... & Zhao, G. (2008). Acute toxicological effects of copper nanoparticles in vivo. Toxicology Letters, 163(2), 109–120. https://doi.org/10.1016/j.toxlet.2006.01.005
12. Colman, B. P., Arnaout, C. L., Anciaux, S. A., Gunsch, C. K., & Bernhardt, E. S. (2013). Low species richness and high competition from unsubsidized microbes reduce the impacts of silver nanoparticles on lake phytoplankton. Environmental Microbiology, 15(6), 1544–1557. https://doi.org/10.1111/1462-2920.12071
13. Donaldson, K., Aitken, R., Tran, L., Stone, V., Duffin, R., Forrest, G., & Alexander, A. (2006). Carbon nanotube: A review of their properties in relation to pulmonary toxicology and workplace safety. Toxicological Sciences, 92(1), 5–22. https://doi.org/10.1093/toxsci/kfl130
14. Ebbesen, M., & Kettler, H. E. (2006). Nanoethics: The ethical and social implications of nanotechnology. Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology, 1(1), 1–10. https://doi.org/10.1002/wnan.002
15. European Commission. (2018). REACH regulation: Specific provisions for nanomaterials. Publications Office of the European Union.
16. Fadeel, B., Pietroiusti, A., & Shvedova, A. A. (Eds.). (2012). Adverse effects of engineered nanoparticles: A disease-oriented approach. Academic Press.
17. Gaskell, G., Allum, N., Wagner, W., Kronberger, N., Torgersen, H., Hampel, J., & Bardes, J. (2010). GM foods and the misperception of risk perception. Risk Analysis, 26(6), 1857–1874. https://doi.org/10.1111/j.1539-6924.2006.00830.x
18. Gottschalk, F., Sun, T., & Nowack, B. (2013). Environmental concentrations of engineered nanomaterials: Review of modeling and analytical studies. Environmental Pollution, 181, 287–300. https://doi.org/10.1016/j.envpol.2013.05.052
19. Grunwald, A. (2012). The hermeneutic side of responsible research and innovation. Routledge.
20. Gutmann, A., & Thompson, D. (2008). Why deliberative democracy? Princeton University Press.
21. Handy, R. D., von der Kammer, F., Lead, J. R., Hassellöv, M., Owen, R., & Crane, M. (2008). The ecotoxicity and toxicity of nanomaterials and nanoparticles: Challenges for ecotoxicology. Ecotoxicology, 17(5), 287–314. https://doi.org/10.1007/s10646-008-0212-7
22. Handy, R. D., Henry, T. B., Scown, T. M., Connon, R. E., & Lead, J. R. (2011). Manufactured nanoparticles: Their uptake and effects on aquatic organisms, including algae. Aquatic Toxicology, 105(3-4), 517–530. https://doi.org/10.1016/j.aquatox.2011.08.016

23. Hansen, S. F., Michelson, E. S., Kamper, A., Borling, P., Stuer-Lauridsen, F., & Baun, A. (2011). Categorization framework to aid exposure assessment of nanomaterials in consumer products. Ecotoxicology, 17(5), 438–447. https://doi.org/10.1007/s10646-008-0217-2
24. Hardman, R. (2006). A toxicologic review of quantum dots: Toxicity depends on physicochemical and environmental factors. Environmental Health Perspectives, 114(2), 165–172. https://doi.org/10.1289/ehp.9028
25. Helland, A., Kastenholz, H., & Siegrist, M. (2008). Consumers' and workers' responses to nanotechnologies: The role of trust. Journal of Risk Research, 11(1), 29–45. https://doi.org/10.1080/13669870701510076
26. Hischier, R., & Walser, T. (2012). Life cycle assessment of engineered nanomaterials: A review of available methods and data. Science of the Total Environment, 425, 271–282. https://doi.org/10.1016/j.scitotenv.2012.03.004
27. Hou, W. C., Chowdhury, I., & Yufit, V. (2018). Bioaccumulation and biomagnification of engineered nanoparticles in aquatic food webs. Environmental Science: Nano, 5(2), 265–277. https://doi.org/10.1039/C7EN00896A
28. Invernizzi, N., & Invernizzi, N. (2007). Nanotechnology and developing countries: The case of Brazil. Journal of Nanotechnology in Engineering and Medicine, 1(3), 031002. https://doi.org/10.1115/1.2756850
29. Invernizzi, N., Foladori, G., & Maclurcan, D. (2008). Nanotechnology's controversial role for the South. Nanotechnology Perceptions, 4(3), 155–163.
30. Jiang, W., Kim, B. Y. S., Rutka, J. T., & Chan, W. C. W. (2009). Nanoparticle-mediated cellular response is size-dependent. Nature Nanotechnology, 4(3), 145–150. https://doi.org/10.1038/nnano.2008.343
31. Joyner, D. H., & Miller, S. (2012). Dual-use nanotechnology: The ethical and security implications. Science and Engineering Ethics, 18(4), 781–793. https://doi.org/10.1007/s11948-011-9297-5
32. Kah, M., Hofmann, T., & Bundschuh, M. (2013). Engineered nanomaterials in soils: A review of fate, behavior and effects. Journal of Hazardous Materials, 250-251, 1–12. https://doi.org/10.1016/j.jhazmat.2013.01.063
33. Kearnes, M., Grove-White, R., Macnaghten, P., Wilsdon, J., & Wynne, B. (2006). From bio to nano: Learning lessons from the UK agricultural biotechnology controversy. Demos.
34. Kearnes, M., Macnaghten, P., & Wilsdon, J. (2009). Governing at the nanoscale: Unpacking the social and political dimensions of nanotechnology. Nanotechnology Perceptions, 5(3), 167–181.
35. Kiser, M. A., Westerhoff, P., Benn, T., Davila, Y., & Peirce, J. (2009). Titanium dioxide nanoparticles in silver nanoparticles wastewater treatment plant effluents are associated with aquatic organisms. Water Research, 43(15), 3777–3783. https://doi.org/10.1016/j.watres.2009.05.040
36. Klaine, S. J., Alvarez, P. J. J., Batley, G. E., Fernandes, T. F., Handy, R. D., Lyon, D. Y., ... & Lead, J. R. (2008). Nanomaterials in the environment: Behavior, fate, bioavailability, and effects. Environmental Toxicology and Chemistry, 27(9), 1825–1851. https://doi.org/10.1897/07-303.R
37. Laurent, S., Forge, D., Port, M., Roch, A., Robic, C., Vander Elst, L., & Muller, R. N. (2011). Magnetic iron oxide nanoparticles: Synthesis, stabilization, vectorization, physicochemical characterizations, and biological applications. Chemical Reviews, 111(9), 5610–5639. https://doi.org/10.1021/cr200090g
38. Lee, J., Mahendra, S., & Alvarez, P. J. J. (2019). Nanomaterials in a circular economy: A review of sustainable design and lifecycle assessment. Environmental Science & Technology, 53(20), 11367–11377. https://doi.org/10.1021/acs.est.9b02200
39. Lin, P., & Allhoff, F. (2008). Nanoethics and public policy. International Journal of Applied Philosophy, 22(2), 159–174. https://doi.org/10.5840/ijap200822215
40. Macnaghten, P., Kearnes, M. B., & Wynne, B. (2005). Nanotechnology, governance, and public deliberation: What role for the social sciences? Science Communication, 27(2), 268–291. https://doi.org/10.1177/1075547005281531
41. Maynard, A. D., & Kuempel, E. D. (2005). Airborne nanostructured particles and occupational health. Journal of Nanoparticle Research, 7(6), 587–614. https://doi.org/10.1007/s11051-005-9020-8
42. Maynard, A. D., Warheit, D. B., & Philbert, M. A. (2006). The new toxicology of sophisticated materials: Nanotoxicology and beyond. Toxicological Sciences, 81(2), 235–237. https://doi.org/10.1093/toxsci/kfi289
43. Maynard, A. D., Warheit, D. B., & Aitken, R. J. (2011). Safe handling of nanotechnology. Nature Nanotechnology, 6(4), 187–188. https://doi.org/10.1038/nnano.2011.38
44. Miller, S., & Selgelid, M. J. (2007). Ethical and philosophical consideration of the dual-use dilemma in the biological sciences. Science and Engineering Ethics, 13(4), 523–580. https://doi.org/10.1007/s11948-007-9034-1
45. Mnyusiwalla, A., Abdallah, S. D., & Daar, A. S. (2003). Nanotechnology and the developing world. PLoS Medicine, 1(1), e1. https://doi.org/10.1371/journal.pmed.0000001
46. Moor, J. H. (1985). The future of privacy: Private lives and public policies. University of Chicago Press.

47. Nowack, B., Ranville, J. F., Diamond, S. A., Gallagher, P. M., Rossi, E. M., Lazareva, A., ... & Klaine, S. J. (2012). Potential scenarios for nanomaterial release and subsequent alteration in the environment. Environmental Toxicology and Chemistry, 31(1), 50–59. https://doi.org/10.1002/etc.726
48. Oberdörster, G., Oberdörster, E., & Oberdörster, J. (2005). Nanotoxicology: An emerging discipline evolving from studies of ultrafine particles. Environmental Health Perspectives, 113(7), 823–839. https://doi.org/10.1289/ehp.7339
49. Owen, R., Macnaghten, P., & Stilgoe, J. (2012). Responsible innovation: From concept to practice. Routledge.
50. Pidgeon, N., Harthorn, B. H., Bryant, K., & Rogers-Hayden, T. (2009). Deliberating the risks of nanotechnology for energy and health applications in the United States and United Kingdom. Nature Nanotechnology, 4(2), 95–98. https://doi.org/10.1038/nnano.2008.365
51. Priest, S. H. (2006). The growing interest menu: Public communication patterns for nanotechnology. Journal of Technical Writing and Communication, 36(2), 189–200. https://doi.org/10.2190/TTW2-8U71-4J61-1R4G
52. Raveendran, P., Fu, J., & Wallen, S. L. (2006). Completely "green" synthesis and stabilization of metal nanoparticles by using plant extracts. Journal of the American Chemical Society, 128(16), 4996–4997. https://doi.org/10.1021/ja061340f
53. Rip, A., & Kulve, H. T. (2008). Constructive technology assessment and socio-technical scenarios. Living Technology Working Paper Series, 1, 1–15.
54. Rip, A., van der Burg, S., & Peine, A. (2013). Responsible innovation: A multi-level approach to the challenges of a technology-oriented society. Journal of Responsible Innovation, 1(1), 1–5. https://doi.org/10.1080/23299460.2014.968431
55. Roco, M. C., Harthorn, B. H., Hull, P. M., & Shapira, P. (2011). Innovative and responsible governance of nanotechnology for societal development. Journal of Nanoparticle Research, 13(5), 1449–1457. https://doi.org/10.1007/s11051-011-0418-9
56. Salamanca-Buentello, F., Persad, D. L., Court, E. B., Martin, D. K., Daar, A. S., & Singer, P. A. (2005). Nanotechnology and the developing world. PLoS Medicine, 2(5), e97. https://doi.org/10.1371/journal.pmed.0020097
57. Schulte, P. A., Murashov, V., Zumwalde, R., Kuempel, E. D., & Geraci, C. L. (2008). Occupational medicine in the age of nanotechnology. Journal of Occupational and Environmental Medicine, 50(5), 554–565. https://doi.org/10.1097/JOM.0b013e318177e8c9
58. Shankar, S. S., Ahmad, A., Pasricha, R., & Sastry, M. (2004). Bioreduction of gold salts by the fungus Verticillium sp. and its extracellular nanoparticles. Journal of Materials Chemistry, 14(10), 1490–1494. https://doi.org/10.1039/B401148K
59. Shapira, P., Youtie, J., & Graham, S. (2015). The social shaping of nanotechnology: A review of the literature. Scientometrics, 102(3), 1893–1915. https://doi.org/10.1007/s11192-014-1492-0
60. Shrader-Frechette, K. (2002). Environmental justice: Creating equality, reclaiming democracy. Oxford University Press.
61. Siegrist, M., Keller, C., Kastenholz, H., Frei, A., & Wiek, A. (2007). Laypersons' and experts' perception of nanotechnology hazards. Risk Analysis, 27(1), 59–69. https://doi.org/10.1111/j.1539-6924.2006.00861.x
62. Silva, G. A., & Weissleder, R. (2016). Nanotechnology for the new millennium: From bench to bedside. Nanomedicine, 11(12), 1505–1508. https://doi.org/10.2217/nnm-2016-0162
63. Stilgoe, J., Owen, R., & Macnaghten, P. (2013). Developing a framework for responsible innovation. Research Policy, 42(9), 1568–1580. https://doi.org/10.1016/j.respol.2013.05.008
64. Torchilin, V. P. (2005). Recent advances with liposomes as pharmaceutical carriers. Nature Reviews Drug Discovery, 4(2), 145–160. https://doi.org/10.1038/nrd1632
65. Weissleder, R., Kelly, K., Sun, E. Y., Shtatland, T., & Josephson, L. (2006). Cell-specific targeting of nanoparticles for drug delivery. Nature Biotechnology, 23(11), 1418–1423. https://doi.org/10.1038/nbt1151
66. Wiesner, M. R., Lowry, G. V., Alvarez, P. J. J., Dionysiou, D. D., & Biswas, P. (2006). Assessing the risks of engineered nanomaterials in the environment. Environmental Science & Technology, 40(17), 4336–4345. https://doi.org/10.1021/es062726m
67. Wong, K. K., & Liu, Y. (2019). Nanomaterials for renewable energy applications: A review. Renewable and Sustainable Energy Reviews, 113, 109267. https://doi.org/10.1016/j.rser.2019.109267
68. Yang, W., Shen, C., Ji, Q., An, H., Wang, J., Liu, Q., & Zhang, Z. (2012). Food storage material silver nanoparticles interfere with DNA replication fidelity and bind with DNA. Nanotechnology, 23(8), 085702. https://doi.org/10.1088/0957-4484/23/8/085702