Deep Science Publishing
https://doi.org/10.70593/978-93-49307-12-4_13

Chapter 13

Regulatory Frameworks and Biosafety Protocols of Nanomaterials in Agro-Based Applications

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Abstract: Nanotechnology has evolved into a feasible and exciting approach for the growth of the agro-sector by using nanoparticles as a carrier system: pest/disease prevention, post-harvest storage, nutritional delivery, genetic alteration of plants for crop enhancement. In agriculture, it could be employed in numerous ways, including as the development of nanoscale instruments that boost productivity, improve the safety and quality of food, maximize the use of water and nutrients, and generate nanoscale delivery systems for fertilizers, development regulators, and pesticides. To satisfy the global food demand, markets already feature nano-based items like food packaging, agrochemicals, nutrients encapsulated, and antimicrobial agents. Consequently, numerous techniques have been applied to regulate nano-based products in food, feed, and industry. Several ethical questions must be considered to ensure the appropriate application of nanotechnology in agriculture and guarantee of correct development. Many nations have been actively looking around to see whether their legal systems fit for handling nanotechnologies. Here we have placed many national rules for nano-based agricultural products, from feed to food, together with worldwide safety assessment policies and laws.

Keywords: Nanotechnology, risk assessment, agriculture, environmental safety, regulations.

Citation: Singh, A.P., Singh, K.K., Kumari, B. & Kumar, P. (2025). Regulatory Frameworks and Biosafety Protocols of Nanomaterials in Agro-Based Applications. In *Eco-Friendly Nanotechnology: Harnessing Small-Scale Technologies for a Cleaner and Healthier Planet* (pp. 170-188). Deep Science Publishing. https://doi.org/10.70593/978-93-49307-12-4_13

1 Introduction

Climate change, population growth, and the loss of arable land are all contributing factors to the increase in the world's food consumption (Rosenzweig *et al.*, 2020; Singh *et al.*, 2021). The UN projects a 34% increase by 2050 (UN, 2019). Conventional breeding improves crops but cannot introduce novel traits (Arya *et al.*, 2020). Modern biotechnologies like genetic engineering, RNA interference, and CRISPR/Cas help enhance crop resilience (Arya *et al.*, 2021a). Nanobiotechnology enables biomolecule delivery via nanocarriers, overcoming plant cell wall barriers (Arya *et al.*, 2021b). Though researched for 50 years, its application is now expanding (Mukhopadhyay, 2014; Pramanik *et al.*, 2020). Nanotechnology-based solutions, including nano-fertilizers, pesticides, and biosensors, improve crop sustainability (Usman *et al.*, 2020). Nanocarrier-based genetic modification has been demonstrated in crops like rice, maize, and wheat (Demirer *et al.*, 2019). While nanotechnology in agriculture holds great potential, safety concerns surrounding human health, environmental effect, and regulatory supervision remain crucial. The US, Europe, China, India, Canada, and Australia are among the nations that have created regulatory frameworks to evaluate the advantages and disadvantages of genetically modified crops based on nanotechnology. These regulations aim to provide safety guidelines and legislation for the proper use of nanotechnology in plant genetic engineering on a global scale.

2 Safety-regulations for nanotechnology

Nanotechnology is increasingly used in agriculture to enhance crop growth, soil quality, and nutrient uptake while enabling targeted pesticide and herbicide delivery (Prasad *et al.*, 2014; Singh *et al.*, 2021). Nano-fertilizers and nano-pesticides help reduce agrochemical use and improve crop resilience (Kah *et al.*, 2013; Gogos *et al.*, 2012). Nanoparticles also aid in soil remediation by breaking down pollutants (Dimkpa & Bindraban, 2018). However, concerns exist over potential environmental and health risks, including bioaccumulation, toxicity to non-target organisms, and soil microbial disruption (Khot *et al.*, 2020; He *et al.*, 2019). Regulatory bodies like FAO, EFSA, and EPA have established safety guidelines, emphasizing toxicity assessments and environmental impact evaluations (Kookana *et al.*, 2014). To ensure safe application, research should focus on eco-friendly nanotechnology using biodegradable and non-toxic materials.

3 United States of America

Nanotechnology-based agricultural crops in the USA are controlled by several government agencies, including the FDA, EPA, and USDA. These agencies aim to ensure that nanotechnology-based products are safe for human consumption, environmentally sustainable, and compliant with existing regulations (Hannon *et al.,* 2015). The FDA oversees food and dietary supplements, ensuring that nanomaterials used in these products meet safety standards before they reach consumers (Powell *et al.,* 2016). Meanwhile, the EPA assesses the environmental risks of nanomaterials used in pesticides and other agricultural applications (Kookana *et al.,* 2014). The USDA, through programs such as the National Organic Program (NOP), regulates the use of nanotechnology in organic and conventional agricultural practices (Scott & Chen, 2017).

The US Food and Drug Administration has already authorized the use of a number of nanomaterials in food and agricultural applications. Products like sweets, chewing gum, and powdered sugar frequently contain titanium dioxide as a whitening agent (Powell *et al.,* 2016). In powdered foods such as coffee creamer, silica nanoparticles act as anti-caking agents (U.S. Food & Drug Administration, 2020). Iron oxide is utilized as a food pigment, while zinc oxide has been approved as a food colorant and dietary supplement (U.S. Food & Drug Administration, 2020). While these materials have been deemed safe, ongoing research and risk assessment efforts are essential to evaluate potential long-term health and environmental effects (Ranjan *et al.,* 2014).

3.1 Key Laws and Regulations in USA

Several key laws and regulations guide the development, approval, and monitoring of nanotechnology-based agricultural products in the United States.

3.1.1 The Toxic Substances Control Act (TSCA): The EPA oversees the regulation of chemical substances, including nanomaterials, under TSCA. Companies must provide safety data on potential human and environmental health impacts before introducing new nano-enabled agricultural products (Hansen *et al.,* 2018).

3.1.2 The Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA): This law governs the registration and use of pesticides containing nanomaterials. Manufacturers must demonstrate their safety and efficacy before obtaining regulatory approval from the EPA (Kah *et al.,* 2018).

3.1.3 The Food, Drug, and Cosmetic Act (FD&C Act): Under this act, the FDA regulates the safety of food and cosmetic products that incorporate nanotechnology. Manufacturers must provide detailed information on the properties and behavior of nanomaterials used in these products to ensure safety (U.S. FDA, 2018).

3.1.4 The National Organic Program (NOP): The USDA establishes standards for organic labeling, though it does not explicitly regulate nanomaterials. However, organic producers must comply with broader federal regulations on nanotechnology use in agricultural production (Scott & Chen, 2017).

3.1.5 The Nanotechnology Research and Development Act (NRDA): This act directs federal agencies to collaborate on nanotechnology research and development. It aims to enhance understanding of nanotechnology risks and benefits, ensuring that appropriate safety measures and regulatory frameworks are in place (Roco, 2011).

3.2 Safety Measures and Industry Guidelines in USA

In addition to regulations, various safety measures help ensure the responsible use of nanotechnology in agriculture.

3.2.1 Conducting Rigorous Safety Testing: Companies must perform extensive toxicity testing and risk assessments to evaluate the potential impacts of nanomaterials on human health and the environment (Kookana *et al.*, 2014).

3.2.2 Labeling Requirements: Proper labeling of products containing nanomaterials is crucial to inform consumers about their composition, potential risks, and safe usage guidelines. Regulatory agencies such as the FDA encourage manufacturers to disclose information about nanomaterial properties, including particle size, shape, and reactivity, to facilitate risk assessment (U.S. FDA, 2018).

3.2.3 Environmental Impact Assessments: To mitigate potential ecological risks, companies are encouraged to conduct environmental risk assessments. These assessments evaluate nanoparticle interactions with soil, water, and living organisms, ensuring that they do not disrupt natural ecosystems (Hansen *et al.*, 2018).

3.2.4 Training and Risk Management: Proper training of employees on the handling, storage, and disposal of nanomaterials is essential to prevent occupational exposure and environmental contamination. Best practices include wearing protective equipment, following established safety protocols, and implementing waste management strategies (Scott & Chen, 2017).

The regulation of nanotechnology-based agricultural products in the United States is a continuously evolving field. As research advances, regulatory agencies must adapt to emerging findings on the potential benefits and risks associated with nano-enabled products. Companies operating in this sector must remain informed about the latest legal requirements, safety protocols, and risk assessment strategies to ensure compliance and consumer safety. While nanotechnology holds great promise for enhancing agricultural productivity and sustainability, continued research, stringent regulations, and collaborative efforts between scientists, policymakers, and industry stakeholders will be essential in shaping its responsible use (Hannon *et al.*, 2015; Ranjan *et al.*, 2014).

4 United Kingdom

A number of government organizations, including FSA, DEFRA, and HSE, are in charge of regulating agricultural goods based on nanotechnology in the United Kingdom. The safe handling and application of nanomaterials in industrial contexts, including agriculture, is greatly aided by the HSE. First released by the HSE in 2011, the Nanotechnology Safety Guidance offers thorough advice for sectors using nanomaterials with a focus on risk mitigation techniques, exposure limits, and occupational safety (Health & Safety Executive, 2011).

The FSA is primarily responsible for food safety and quality, including assessing the risks associated with nanotechnology in food products. In 2014, the FSA published a detailed report on the safety of nanomaterials in food, highlighting the need for rigorous risk assessment before commercialization (Food Standards Agency, 2014). This report also emphasized the importance of transparency in food labeling to ensure consumer awareness regarding the presence of nanomaterials in food products. DEFRA has released particular guidelines on the usage, processing, and disposal of nanomaterials in agricultural settings in addition to food safety. The most recent scientific developments in comprehending the health and environmental hazards connected to agricultural nanotechnology are reflected in this guidance, which was last revised in 2018 (DEFRA, 2018). Overall, as scientific research reveals more details about the possible risks and advantages, new criteria are issued, resulting in a constantly changing regulatory framework for agricultural goods based on nanotechnology in the UK. The UK regulatory landscape remains aligned with broader European Union (EU) regulations, ensuring consistency in safety measures, risk assessments, and compliance standards across the region (Koehler *et al.*, 2020).

4.1 European Regulatory Framework: Pesticides, fertilizers, and animal feed additives are among the agri-products based on nanotechnology that are subject to strict regulations in Europe to protect the environment and public health. In order to undertake scientific risk assessments and offer recommendations about the safety, toxicity, and regulatory compliance of nanomaterials, the European Food Safety Authority (EFSA) and the European Chemicals Agency (ECHA) are essential (EFSA Scientific Committee, 2011; ECHA, 2012).

Several significant European legislations govern the use of nanomaterials in agriculture, food safety, and environmental protection. Regulation (EC) No 1107/2009 requires that plant protection products, including nano-based pesticides, undergo extensive research for toxicity and environmental impact before market clearance. Regulation (EC) No 396/2005 defines maximum residue limits for pesticides, ensuring consumer health by regulating both conventional and nano-based compounds in food and feed. Regulation (EC) No 1935/2004 provides safety criteria for food-contact materials, limiting hazardous migration of nanoparticles into food items. Similarly, Regulation (EC) No 767/2009 necessitates comprehensive review of nano-based feed additives to protect animal health, human consumers, and ecosystems. Lastly, Regulation (EU) No 2019/1009 establishes safety and quality criteria for CE-marked fertilizers, ensuring that nano-enabled fertilizers do not adversely influence soil, plants, or water systems. Collectively, these laws provide a comprehensive framework for the appropriate use of nanotechnology in agriculture and food-related applications.

4.2 Guidelines and Recommendations from European Agencies: Beyond these regulations, several European agencies, including ECHA and EFSA, have issued additional safety assessment guidelines for nanomaterials used in agricultural products. EFSA has developed a scientific opinion on risk assessment methodologies for engineered nanomaterials in food and feed, emphasizing the need for case-by-case evaluations due to the unique properties of nanoparticles (EFSA Scientific Committee, 2018). Similarly, ECHA has proposed detailed guidance on the registration and classification of nanomaterials under the EU's Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH) regulation, ensuring their safe use and compliance with EU laws (ECHA, 2021).

The UK and European regulating guidelines for nanotechnology-based agricultural products are predicated on extensive safety evaluations, strict approval processes, and constant scientific research. As nanotechnology in agriculture continues to grow, both regulatory agencies and industry stakeholders must remain diligent in analysing possible dangers and updating rules accordingly. Collaborative efforts between government agencies, research institutes, and agricultural sectors are vital to assuring the safe and sustainable use of nanotechnology in food production, animal feed, and environmental management (Koehler *et al.,* 2020).

5. Canada

In Canada, the regulation of nanotechnology-based agricultural products is governed by multiple laws and regulatory frameworks that ensure consumer safety, environmental protection, and product efficacy. Various governmental agencies, including Health Canada, Environment and Climate Change Canada (ECCC), and the Canadian Food Inspection Agency (CFIA), oversee the enforcement of these regulations. Nanomaterials used in agriculture, such as nano-pesticides, nano-fertilizers, and nano-based food additives, are subject to comprehensive risk assessments, labeling requirements, and safety evaluations before they can be marketed and distributed (Chaudhry *et al.,* 2017). The following key regulations outline the legal framework for nanotechnology-based agri-products in Canada.

5.1 Canadian Environmental Protection Act: The CEPA serves as the primary federal legislation for assessing and managing the risks associated with nanotechnology-based products, including agricultural applications. The act provides the legal context for regulating new materials, including engineered nanomaterials, under the New Substances Notification Regulations (NSNR). Under this regulation, manufacturers and importers of nanomaterials must provide comprehensive toxicity data, environmental impact assessments, and risk management plans before their products are approved for use (Chemicals & Polymers, 2015). Health Canada and Environment and Climate Change Canada work collaboratively to evaluate the potential human health and ecological risks posed by nanomaterials, ensuring that nano-enabled agricultural products meet stringent safety standards (Hendren *et al.*, 2015).

5.2 Food and Drugs Act: The FDA is Canada's primary legislation for certifying the safety, value, and proper labeling of food products, drugs, and cosmetics, including those incorporating nanotechnology. This act empowers Health Canada to conduct scientific risk assessments on nano-enabled food ingredients, food contact materials, and food additives before they can be introduced into the market (Bouwmeester *et al.*, 2018). Additionally, the FDA requires clear labeling of food products containing nanomaterials, ensuring that consumers have adequate information about the presence and potential risks of nanoscale ingredients. Health Canada has established guidelines for the risk assessment of engineered nanomaterials in food, emphasizing the need for case-by-case evaluations based on toxicological data, exposure levels, and long-term safety considerations (Miller & Wickson, 2015).

5.3 Pest Control Products Act: The PCPA regulates pesticides and pest regulator products, including those that utilize nanotechnology. The Pest Management Regulatory Agency (PMRA), a division of Health Canada, is responsible for evaluating the safety, efficacy, and environmental impact of nano-enabled pesticides before granting approval for their use in Canada (Kuzma, 2018). Under the PCPA, companies seeking to register nano-based pesticides must provide detailed information on nanoparticle properties, potential toxicity, bioaccumulation risks, and environmental persistence (Khot *et al.*, 2012). The risk assessment process includes evaluating the potential exposure to humans, pollinators, and soil microbiota, ensuring that nano-pesticides do not pose unforeseen environmental or health hazards (Simonin & Richaume, 2015).

5.4 Canada Agricultural Products Act: The CAPA governs the inspection, grading, and marketing of agricultural products, including those incorporating nanotechnology. The Canadian Food Inspection Agency (CFIA) is responsible for enforcing quality control standards, conducting inspections, and ensuring that nano-enabled agricultural products meet regulatory safety requirements (Joseph & Morrison, 2006). CAPA ensures that nano-fertilizers, nano-coated seeds, and other nano-enabled agricultural inputs comply with strict guidelines on contamination levels, labeling accuracy, and safety for human consumption (Parisi *et al.*, 2015). The act also sets out standards for international trade, ensuring that Canadian nano-enabled agri-products meet global safety and quality benchmarks (Gruère, 2012). Canada's regulatory framework for nanotechnology-based agricultural products is built upon stringent safety assessments, environmental impact evaluations, and consumer protection measures. As research in nanotechnology and agricultural sciences continues to advance, Canadian regulators must remain proactive in updating guidelines and risk assessment protocols to address emerging challenges and opportunities in the field (Rickerby & Morrison, 2018).

6. Australia

Australia has a comprehensive regulatory framework governing the use of nanotechnology in agriculture, ensuring that nano-enabled pesticides, fertilizers, veterinary medicines, and food products meet strict safety, environmental, and health standards. The country follows a precautionary approach, with multiple regulatory agencies responsible for risk assessment, approval, and post-market monitoring of nanotechnology-based agricultural products (Bartholomaeus, 2011). Key regulatory bodies include the APVMA, FSANZ, SWA, and TGA. The following sections detail the primary regulations and guidelines for nanotechnology-based agricultural products in Australia.

6.1 Australian Pesticides and Veterinary Medicines Authority: The APVMA is the primary regulatory body responsible for the approval, registration, and monitoring of agrochemicals, including nano-based pesticides and veterinary medicines. The APVMA assesses the potential human health and environmental risks of nanotechnology-based agricultural chemicals before they can be legally marketed in Australia. In 2014, the APVMA published a guidance document outlining the data requirements, risk assessment procedures, and safety protocols for nano-enabled pesticides (APVMA, 2014). This framework ensures that nanopesticides do not pose unintended risks to ecosystems, farmers, or consumers (Kah *et al.*, 2018). The APVMA also collaborates with international regulatory agencies, such as the European Chemicals Agency (ECHA) and the United States Environmental Protection Agency (EPA), to align risk assessment methodologies and improve regulatory coherence (Gogos *et al.*, 2012).

6.2 Food Standards Australia New Zealand: FSANZ is responsible for ensuring the safety, quality, and labeling compliance of food products, counting those that contain engineered nanomaterials (FSANZ, 2015). In 2015, FSANZ conducted a comprehensive risk calculation on titanium dioxide (TiO_2) nanoparticles in food, concluding that current exposure levels do not pose a significant health risk (FSANZ, 2015). However, FSANZ continues to monitor emerging scientific evidence on nanoparticles in food and has proposed a case-by-case risk assessment approach for novel nanomaterials (Duncan, 2011). Under Australia's Food Standards Code, manufacturers are required to disclose the presence of engineered nanomaterials in food products, ensuring that consumers are informed about their dietary choices (FAO/WHO, 2013).

6.3 Work Health and Safety Laws and NICNAS: Australia's WHS laws mandate that employers take essential safeguards to keep workers from potential exposure to hazardous nanomaterials (Safe Work Australia, 2019). This includes proper ventilation, protective equipment, and training programs for individuals handling nanopesticides, nano-fertilizers, and engineered nanomaterials in agriculture (Schulte *et al.,* 2016).

The NICNAS plays a crucial role in providing guidance on the safe handling, labeling, and disposal of industrial nanomaterials, including those used in agricultural applications (NICNAS, 2019). In 2019, Safe Work Australia released updated guidelines addressing the occupational hazards associated with nanotechnology, emphasizing the need for continuous risk assessments and exposure monitoring in workplaces (Safe Work Australia, 2019).

6.4 Therapeutic Goods Administration: The TGA oversees the regulation of healing goods, including nano-enabled veterinary medicines, drug formulations, and agricultural biotechnologies (TGA, 2015). In 2015, the TGA issued guidance on the regulatory requirements for medicines containing nanomaterials, outlining toxicity testing, pharmacokinetics studies, and risk-benefit assessments (TGA, 2015). This framework ensures that nano-based veterinary medicines used in livestock and animal health do not pose safety concerns to animals, humans, or the environment (Rizwan *et al.,* 2017). The TGA closely collaborates with international regulatory agencies such as the US FDA and EMA to harmonize risk assessment methodologies for nano-therapeutics (Nowack *et al.,* 2012).

Australia has adopted a proactive and precautionary regulatory approach toward nanotechnology in agriculture, ensuring that nano-enabled pesticides, fertilizers, food additives, and veterinary medicines meet high safety and environmental standards. Agencies such as APVMA, FSANZ, Safe Work Australia, and the TGA play a pivotal role in assessing risks, enforcing compliance, and updating regulatory frameworks in response to new scientific findings (McClements & Xiao, 2017). As nanotechnology continues to advance, Australian regulators must remain vigilant and adaptive to ensure both innovation and consumer protection in the agricultural sector (Rickerby & Morrison, 2018).

7. China

China has established a multi-agency regulatory framework to oversee the safety, quality, and environmental impact of nanotechnology-based agricultural products. Several government bodies, including the MARA, SAMR, NHC and MEE, play critical roles in risk assessment, approval, and post-market surveillance of these products (Zhao *et al.*, 2018). With nanotechnology playing an increasing role in fertilizers, pesticides, food additives, and genetically modified organisms (GMOs), China has developed a set of regulatory measures to ensure consumer safety and environmental sustainability (Niu *et al.*, 2021).

China has put in place a thorough regulatory framework to guarantee the safety of agricultural goods based on nanotechnology and genetically modified organisms (GMOs). By defining approval processes, safety evaluations, and monitoring requirements, the Regulations on the Safety Assessment of Agricultural Genetically Modified Organisms (MARA) lay the groundwork for assessing GM agricultural products, including those that incorporate nanotechnology. To ensure strict pre-market approval for food additives that use nanotechnology for improved bioavailability and preservation, the Safety Requirements for Food and Food Additives Containing Nanomaterials established guidelines for evaluating and labeling nano-enabled food products. The Technical Guidelines for Safety Assessment of Nano-Scale Agricultural Products established procedures for assessing the stability, environmental impact, and risks to human health of nano-pesticides, nano-fertilizers, and nano-coated seeds in recognition of the quick developments in nano-agriculture. Stricter evaluation standards for genetically modified crops, animals, and microorganisms incorporating nanotechnology were enforced by the Administrative Measures for Safety Evaluation of New Varieties of Agricultural GMOs (SAMR Order No. 8 – 2020), further enhancing regulatory oversight and guaranteeing thorough risk assessments prior to market approval. The need for thorough environmental risk analysis, with an emphasis on the effects of nano-based agrochemicals on soil health, water systems, and biodiversity, was further underlined by the Measures for the Administration of Environmental Safety Assessment of Agricultural GMOs (MEE Order No. 12-2021). When taken as a whole, these laws show China's dedication to striking a balance between biosafety, public health, and environmental sustainability with technological progress. China's regulatory structure is anticipated to change as nanotechnology in agriculture advances, tackling new issues in genetic engineering, crop protection, and food production.

8. India

India has developed a multi-agency regulatory framework to oversee the safe development, application, and commercialization of nanotechnology-based agricultural products. Various regulatory bodies, including the Department of Biotechnology (DBT), the Ministry of Environment, Forest and Climate Change (MoEFCC), the Food Safety and Standards Authority of India (FSSAI), and the Indian Council of Agricultural Research (ICAR), play a crucial role in ensuring that nanotechnology-based fertilizers, pesticides, food additives, and genetically engineered crops meet safety and environmental standards (Kumar *et al.,* 2019). Despite growing research and development in agricultural nanotechnology, India's regulatory landscape continues to evolve, requiring more comprehensive and coordinated efforts to establish clear safety guidelines (Sharma *et al.,* 2021).

India has established a comprehensive regulatory framework to govern the use of nanotechnology in agriculture, food safety, and environmental protection. The Environment (Protection) Act, 1986 serves as the overarching legislation that empowers the Ministry of Environment, Forest and Climate Change (MoEFCC) to regulate hazardous substances, including engineered nanomaterials used in agrochemicals. Complementing this, the Hazardous Waste (Management, Handling, and Transboundary Movement) Rules, 2016 mandate industries handling nano-based pesticides and fertilizers to obtain prior authorization for waste disposal and containment, ensuring compliance with international safety standards. The Food Safety and Standards Act, 2006 enables the Food Safety and Standards Authority of India (FSSAI) to regulate nano-based food products, with draft guidelines introduced in 2018 focusing on risk assessment, pre-market approval, and consumer awareness regarding nano-enabled food additives and packaging.

To ensure agricultural safety, the Insecticides Act, 1968 regulates nano-formulated pesticides and insecticides, requiring toxicity and environmental impact evaluations before commercialization, overseen by the Central Insecticides Board & Registration Committee (CIBRC). Similarly, the Seeds Act, 1966 governs seed quality, with ongoing discussions on amendments to address nano-based seed coatings and genetic modifications. The DBT Guidelines on Safety Assessment of Foods Derived from Genetically Engineered Plants and Microorganisms (2017) focus on nano-enabled genetic modifications, ensuring thorough safety evaluations before commercialization. Additionally, the MoEFCC Notification on Manufacture, Storage, and Import of Hazardous Chemicals Rules (1989) enforces strict environmental and safety compliance for agri-based nanomaterials such as nano-fertilizers and nanopesticides.

Further reinforcing nano-regulation, the FSSAI Regulations on Food Additives (2011) set permissible limits and labeling requirements for nano-based preservatives and antimicrobial coatings in food products. The ICAR Guidelines on Nanotechnology Research in Agriculture (2010) promote research into nano-enabled fertilizers, pesticides, and seed treatments while addressing concerns about nanoparticle accumulation in soil and crops. Lastly, the Indian Pharmacopoeia Commission (IPC) Guidelines on Nanoparticle Characterization (2019) establish quality control standards for nanoparticles used in agricultural inputs and food supplements. Together, these regulations create a robust legal framework to balance innovation in nanotechnology with environmental sustainability and public health in India.

India's regulatory framework for nanotechnology-based agricultural products is still evolving, with various government agencies working to establish scientific risk assessment protocols, safety guidelines, and environmental regulations (Sharma *et al.*, 2023). As the adoption of nanotechnology in agriculture increases, there is a growing need for more integrated and well-defined policies to ensure consumer safety, environmental sustainability, and compliance with international regulatory standards (Mukherjee & Das, 2022).

Conclusions

Nanotechnology has transformed agriculture by enhancing crop productivity, pest control, and food quality. Nano-based fertilizers, pesticides, and seed treatments improve nutrient efficiency, stress tolerance, and disease resistance. However, concerns like toxicity and environmental impact must be addressed. Green synthesis methods reduce pollution by using biocompatible materials. Nano-priming boosts seed germination and growth without harming the environment. Controlled synthesis ensures safe and effective nanoparticles. Optimizing dosage and delivery minimizes risks to soil, water, and non-target organisms. Global regulations must evolve with research to ensure safety. Responsible use and eco-friendly innovations will make nanotechnology a sustainable agricultural tool.

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