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Chapter 12

Risk-Benefit Dynamics of Nano-Enabled Technologies in Sustainable Agroecosystems

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Abstract: Nanotechnology has been found evident in handling various predicaments related to agriculture and the environment, including sustainable resource management, urbanization and energy limitations over the years. Thus, the emergence of nano-agrochemicals, including nano-pesticides, nano-fertilizers and nano-sensors, aimed at boosting solubility, enhancing bioavailability and facilitating targeted delivery, along with their controlled release, will offer significant potential precedence such as precise fertilizer application, better pest control, lowered chemical pollution and ultimately higher agricultural yields While the use of agrochemicals has boosted agricultural productivity, it significantly affects the soil and aquatic ecosystems along with their associated flora and fauna species, as well as the health of the farmers and the community-consuming chemically cultivated food unintentionally. However, the evaluation of risk associated with this technology is significantly behind its usage and the dangers associated with unwanted exposure during production or service exploitation of nanoparticles can be mitigated by taking steps once the risks &safe limits of various nanomaterials have been analysed and tabulated. Therefore, it is important to address the assessment of risks and biosafety concerns of agricultural nanotechnology.

Keywords: Nanotechnology, Biosafety risks, Risk assessment, Nano-sensors.

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1 Introduction

Nanotechnology defines the understanding, managing and taking advantage of the special qualities of matter that can arise at scales of one to 100 nanometers. The conception of “nanotechnology” is deduced, in part, from the Greek word “nano”, signifying “dwarf” (Warheit *et al.*, 2008). It has the implicit in making an impact on several agrarian and environmental challenges, such as energy and resource constraints, urbanization, sustainable use of coffers, runoff, and accumulation of fungicides and diseases (Chen and Yada, 2011; Ditta, 2012; Parisi *et al.*, 2015). Nanotechnology may have a substantial impact on sustainable agriculture and precision farming development. These ultimately aim to maximize agricultural output while minimizing input through monitoring environmental variables and applying targeted action (Fraceto *et al.*, 2016; Servin *et al.*, 2015). Once distributed into physico-chemically changing environments, the possible great variety of nano-substances used is still not fully understood. Their distinctive methods of application in agricultural settings require not only a "nano-focused" approach but also targeted "nano-agricultural" strategies for evaluating and managing occupational risks (Kookana *et al.*, 2014).

The potential diversity of nano-substances used in agriculture is not yet fully understood in terms of their toxicity when dispersed in changing physical and chemical environments. Their unique applications in agricultural fields require not only a "nano-focused" approach but also the development of specific "nano-agricultural" strategies for assessing and managing occupational risks effectively. The full extent of the diversity of nano-substances used in agriculture is not yet completely understood, particularly regarding their toxicity in varying physical and chemical environments. To effectively manage occupational risks associated with these substances, it is essential to adopt specialized "nano-agricultural" strategies that go beyond a simple "nano-focused" approach. These strategies should assess the unique applications of nano-materials in agricultural settings.

2 Risk assessment and biosafety concerns of nanotechnology in agriculture

Evaluating risks specific to nanomaterials presents a complex challenge because the assumptions utilized for assessing the risks of traditional chemicals, along with testing methods and modelling frameworks regarding environmental behaviour and potential human absorption, may not be suitable for nano-enabled products (Damalas & Eleftherohotinos, 2011).

Evaluating the impact of agricultural chemicals on human health is a complex task. This complexity arises from the wide variety of substances used, the different mixtures applied in the fields, variations in exposure levels, and the unique geographic and meteorological characteristics of the agricultural areas where these chemicals are used (Pastor, 2003).

3 Hazard Identification & Characterization

The assessment of hazards related to nano-formulation should concentrate on the properties of active ingredient concentrations and the specific nano-components involved. The potential environmental and health hazards of nanoparticles highlight the challenges in interpreting data for effective hazard identification (Krug, 2014). The behaviour and outcome of the nano-component may be similar to that of traditional pesticide formulations if its sole purpose is to prevent the active ingredient from degrading. However, it is crucial to evaluate the potentially hazardous behaviour of pristine, inorganic designed nanoparticles (NPs) from a life-cycle viewpoint when utilising them as efficient fertilisers or insecticides or for soil and water remediation. From their introduction into application fields until the removal of any working residues, the full process should be taken into account in this evaluation (Shatkin & Kim, 2015).

Non-stable NMs in food preparation may degrade or transform into non-nano forms. In such cases, toxicity measurements can follow protocols for non-nano forms, provided solid evidence of solubility is demonstrated. This applies to non-persistent NMs in marketed foods and those transforming before consumption. For unstable intermediates and impurities, levels of natural defects that pose no health risks may be detailed according to US FDA guidelines & For nanomaterials (NMs) that are fully degraded in the gastrointestinal tract without being absorbed in their nano form, the hazard characterization can be less stringent. In such cases, data for the non-nano form can be used instead. However, this approach must be supported by in vitro genotoxicity tests and in vivo testing for local effects. If there are no existing regulations for the non-nano form, relevant regulatory guidelines should be referenced (Amenta *et al.,* 2015). Hazards are potential sources of harm associated with engineered nanomaterials (NMs) in agricultural systems.

The use of nanomaterials in agriculture introduces both intentional and unintentional sources of exposure. Nano-agrochemicals, such as nano-encapsulated pesticides and nanosensors for soil monitoring, are deliberately applied to enhance efficiency. However, accidental leakage and the degradation of nanomaterial-containing products can lead to unintentional environmental contamination (Liu *et al.,* 2008). These nanomaterials enter soil and water systems, causing bioaccumulation in crops and potential human exposure through ingestion or occupational contact during application (Oberbek *et al.,* 2019; Armstead *et al.,* 2016). Assessing toxicity is crucial, as nanomaterials can reduce germination rates, induce oxidative stress, and alter nutrient uptake in plants. In vitro and in vivo studies help evaluate cellular toxicity, organ-specific effects, and long-term exposure risks. Additionally, soil microbiome disruption is a concern, as nanoparticles may negatively affect nitrogen-fixing bacteria and other beneficial microbes. Ecotoxicological risks extend to pollinators, particularly bees, which may suffer from exposure to nano-pesticides (Khot *et al.*, 2012; Ankley *et al.*, 2009; Ivacoli *et al.*, 2012; Pérez *et al.*, 2009). Ensuring the safe use of nanotechnology in agriculture requires comprehensive risk assessment and regulatory oversight.

4 Hazard Characterization

Physico-chemical Properties: The shape, size, surface charge, and solubility of nanoparticles (NPs) significantly govern their reactivity and bioavailability. For instance, smaller nanoparticles may more readily penetrate the cell walls of plants (Shin *et al.,* 2015).

4.1 Mechanisms of Toxicity

The mechanisms through which NPs exert toxicity include oxidative stress, which involves the generation of reactive oxygen species (ROS) that can damage cellular structures. Genotoxicity is another critical concern, particularly with nanoparticles such as titanium dioxide (TiO_2) & silver (Ag), which have the potential to cause DNA damage. Furthermore, bioaccumulation is a significant issue, as certain nanoparticles, such as cerium oxide NPs, may persist in soil and accumulate within root tissues. The observed increase in growth rate may be attributed to the photo-sterilization and photogeneration of reactive oxygen species, such as superoxide and hydroxide anions, facilitated by titanium dioxide nanoparticles (TiO_2-NPs). These reactive species may boost the stress resistance of seeds and enhance the penetration of capsules, which in turn aids in the absorption of water and oxygen crucial for swift germination. In comparison, multi-walled carbon nanotubes (CNTs) can infiltrate seeds and increase the germination rate by enhancing both water absorption and the overall efficiency of resource use in plants (Khodakovskaya *et al.,* 2009; M. V. Khodakovskaya *et al.,* 2012).

4.2 Dose-Response Relationships

It is essential to establish threshold levels for harm; for example, high concentrations of zinc oxide (ZnO) nanoparticles have been shown to inhibit plant growth. Additionally, non-linear effects, such as hormesis, should be considered, where low doses may provide beneficial effects while high doses are toxic (Chen *et al.,* 2015).

5 Exposure Assessment

The identification of all potential sources of exposure is pivotal for comprehensively understanding the entire manufacturing process and determining the most likely routes of exposure. This understanding is also essential for selecting the appropriate testing strategy and formulating recommendations regarding risk prevention measures. For instance, employing predictive modelling of the biological effects of nanomaterials is vital for industry stakeholders and policymakers to evaluate the potential hazards associated with the utilization of engineered nanomaterials. The embryonic zebrafish metric (EZ Metric) serves as a screening-level measurement indicative of adverse effects. Utilizing this dataset, we have developed a data mining approach to model the toxic endpoints and assess the overall biological impact of nanomaterials. Data mining techniques, including numerical prediction, can aid analysts in constructing risk assessment models for nanomaterials (Liu *et al.*, 2013).

6 Risk Management

To effectively mitigate potential risks associated with agricultural nanotechnology, a robust management plan must be prioritized, incorporating a clear hierarchy of controls. The proactive implementation of solutions that either eliminate or replace harmful exposures should be the main focus of this approach. Subsequently, the reduction of risks should be achieved through the implementation of administrative controls applicable at every stage of the nanomaterial lifecycle, culminating in the use of personal protective equipment. At the top of the hierarchy of controls, the most effective tactic is to remove or rethink the risks associated with nanomaterials. This strategy guarantees that safety is incorporated into innovation from the outset and is consistent with the timeless ideas of "prevention through design" and "safety by design" (Hjorth *et al.*, 2017).

Green engineering emphasises making choices early in a process or product's design and development phase to maximise impact and cost-effectiveness while protecting human health and the environment (Bergeson, 2013). Green engineering is a holistic approach that considers every stage of a product's life cycle, starting from the initial extraction of raw materials and continuing through the manufacturing process, its usage, and ultimately, the end-of-life phase. This comprehensive perspective on green engineering emphasizes the importance of sustainable practices and the thoughtful management of resources. Coupled with the principles of green nanotechnology, this approach allows stakeholders to proactively identify and address potential hazards that may arise from unforeseen consequences. The industry can play a significant role in this endeavour by providing essential data and product information, as well as sharing expertise in technical, scientific and policy matters (Watson *et al.*, 2011).

7 Risk Governance

Establishing appropriate occupational safety procedures & policies should occur at the outset of any operations involving nanomaterials, rather than being introduced later in response to identified unsafe conditions. Because of the safety issues related to certain nanomaterials and the challenge of making overly broad generalizations due to the vast array of applications within nanotechnology, it is essential to tackle this regulatory gap concerning these xenobiotics. This gap should be addressed by utilizing the results from current projects focused on toxicity testing, decision-making regarding the characterization of nanomaterials and testing procedures, along with data on exposure and precautionary management (Hester *et al.*, 2015). The United States Environmental Protection Agency (EPA) exercises its authority under the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) to register pesticides and has lately suggested classifying recognised conventional chemicals in nanoscale form as "new" for registration (Environmental Protection Agency, 2011).

In Europe, nanoscale pesticide active ingredients and formulations fall under the Plant Protection Products Regulation of EC 1107/2009 (EC, 2009). This law regulates the use and authorisation of pesticides in the European Union and applies to both single and combined products, regardless of their size, shape, or physical condition. It is essential to take into account nanomaterials that exhibit pesticidal action, such as nano-silver, in addition to nano-formulations of conventional active chemicals. Like any other active ingredient, these chemicals must be evaluated, which means that information about their toxicity and environmental fate must be gathered. The ability of current hazard identification and characterisation processes to effectively handle such nano-products and the efficacy of standard protocols in discovering novel or improved attributes remain crucial questions.

Therefore, in order to have a thorough grasp of the properties and toxicological behaviour of nanomaterials, academic institutions, industry representatives, governmental organisations, and stakeholders must work together in concert. This endeavour should include defining their current applications within the field of nano-agriculture as well as identifying potential intended uses. Efforts must concentrate on developing new policies specific to nanomaterials, or effectively applying existing policies to such substances, particularly in the context of nano-agricultural applications. Instead of being applied after dangerous situations have arisen, pertinent occupational safety procedures and policies should be developed before any operations employing nanoparticles begin.

8 Biosafety Concerns of Nanotechnology

Impact on Soil Microbial Communities-Studies has documented more pronounced effects, either inhibitory or stimulatory, on earthworms, plants and soil microbial communities when titanium dioxide (TiO_2) and silver (Ag) engineered nanoparticles (ENPs) were applied to soils in a "wet" form, as compared to "dry" amendments. (Hund-Rinke *et al.,* 2012). Although the amendment technique may affect the fate and behaviour of particles in soil media, there is limited research on the changes in the physicochemical properties of engineered nanoparticles (ENPs) during mixing processes and due to their uneven distribution in soils. Therefore, it is advisable to conduct a characterization of ENPs after their addition to the soil matrix to prevent misunderstandings related to unexpected changes in ENP dissolution and agglomeration, which can subsequently impact particle availability (Servin & White, 2016).

Bioaccumulation in Crops- Nanoparticles (NPs) like cerium dioxide (CeO_2) and zinc oxide (ZnO) which can accumulate in the tissues of edible plants, raising concerns about their potential transfer into the food chain. Once these nanoparticles enter the soil system, they may undergo various biological and geological transformations. These processes ultimately affect the bioavailability and toxicity of the nanoparticles, potentially leading to harmful effects, generating oxidative stress, and allowing for absorption by plants. This poses a possible hazardous to human health through their transfer in the food chain (Chen, 2018; Rajput *et al.,* 2018b; Rajput *et al.,* 2020b; Servin *et al.,* 2016).

8.1 Toxicity to Non-Target Organisms

The use of nano-pesticides presents an opportunity for increased agricultural efficiency; however, it is essential to recognize their potential impacts on beneficial insects, such as pollinators and aquatic organisms due to unintended exposure. Research indicates that nano-pesticides can affect a variety of non-target species, which may be contributing to concerns about global biodiversity loss. While the full extent of these hazards is still being explored, studies suggest that negative effects are more pronounced in temperate regions compared to tropical ones. Moreover, these impacts appear to be consistent in both aquatic and terrestrial environments, even under realistic exposure conditions (Côa *et al.,* 2020). Addressing these concerns will be crucial for sustainable pest management practices moving forward.

8.2 Antibiotic Resistance Promotion

Metallic nanoparticles (e.g., Ag, Cu) can promote horizontal gene transfer among soil bacteria, thereby accelerating the development of antibiotic resistance. When utilizing metallic nanoparticles as antimicrobial agents, bacteria generate nanoresistance, which simultaneously affects the mutation, expression, or transfer of antibiotic resistance genes (ARGs). With the common production and use of metallic nanoparticles, two exposure scenarios highlight their overlap with antibiotics in various environmental contexts (such as water, soil and sludge) as well as in human settings (including agriculture, aquaculture and healthcare facilities) (Zhang *et al.,* 2020; Fang & Pan, 2024).

8.3 Genotoxicity in Plants and Animals

Certain nanoparticles (like, graphene oxide) possess the potential to induce DNA damage in plants and soil organisms, which raises concerns about long-term safety. DNA damage can lead to a higher frequency of sister chromatid exchange (Brachner *et al.,* 2020). The electrical charge on the surface of nanoparticles (whether positive or negative) affects how these nanomaterials interact with subsystems or biological membranes in a watery environment (Singh *et al.,* 2019). It follows that negatively charged particles will be drawn to positively charged surfaces and vice versa. Typically, positively charged nanoparticles are seen as more toxic and may even harm cell membranes. Additionally, they can interact with enzymes, proteins and DNA, increasing the risk of genotoxic effects (Souto *et al.,* 2020).

8.4 Altered Plant Physiology

Nanoparticles (NPs) can disrupt plant metabolic pathways by interfering with photosynthesis. For example, nanoparticles like titanium dioxide (TiO_2), cerium dioxide (CeO_2) and silver (Ag) can accumulate in chloroplasts, which negatively affects light absorption and damages photosynthetic pigments, such as chlorophyll. Additionally, NPs cause an excess of reactive oxygen species (ROS), which can overwhelm the plant's defence mechanisms against these toxins, which include enzymes like superoxide dismutase and catalase. The excess ROS can damage lipids, proteins and DNA, disrupting crucial metabolic pathways such as glycolysis and the Calvin cycle. Growth inhibition is another significant issue. Nanoparticles like zinc oxide (ZnO) and copper oxide (CuO) can adhere to root surfaces, damaging root hairs and reducing the plant's ability to uptake water and nutrients. They may also interfere with phytohormone signalling, which is critical for processes such as cell division and elongation, affecting hormones like auxins and cytokinin. Furthermore, NPs can alter stress responses in plants by modulating the expression of stress-related genes, such as heat shock proteins and mitogen-activated protein kinases (MAP kinases). They may also interfere with important signalling molecules, including nitric oxide (NO) and salicylic acid (SA) (Nafees *et al.*, 2020).

8.5 Synergistic Effects with Environmental Pollutants

Nanoparticles (NPs) can engage with pesticides or heavy metals, enhancing the toxicity within ecosystems. NPs that are smaller than 4.5 μm can penetrate cells or even reach organelles and microplastics/nanoplastics (MPs/NPs) that carry pollutants can cause a range of irreversible harm such as apoptosis, necrosis and autophagy. Nonetheless, the existing findings are inconsistent and the cytotoxic behaviour of MPs/NPs that carry pollutants, along with the toxicity mechanisms, remain poorly understood. An examination of several case studies and data showed that low levels of MPs/NPs often lower the bioavailability of pollutants through adsorption, resulting in decreased toxicity in scenarios of combined pollution; conversely, high levels of MPs/NPs tend to dominate the toxic effects caused by combined toxicity. Hence, toxic interactions might be closely linked to the adsorption capability (Sun *et al.*, 2022).

8.6 Persistence in Ecosystems

Non-biodegradable nanoparticles (e.g., copper nanoparticles, or Cu NPs) can persist in soils, creating long-term ecological risks. Once released into the environment, Cu NPs are expected to initially aggregate with one another (homo-aggregation). However, in the presence of natural colloids, they are more likely to undergo hetero-aggregation with those substances. The increasing use of Cu NPs, particularly in applications where they are directly released into the environment such as antifouling paints & pesticides will lead to greater exposure for organisms. Inhalation of Cu NPs can cause pulmonary inflammation and trigger a strong immune response, even at low concentrations. Therefore, occupational exposure to paints and pesticides containing Cu NPs must be minimized by using appropriate personal protective equipment. This is especially important when handling dry powders of Cu NPs (e.g., during formulation) or when working with aerosolized pesticide formulations (Keller *et al.*, 2017).

8.7 Human Health Risks via Food Chain

The accumulation of nanoparticles (NPs) in crops can pose significant health risks to humans, triggering mechanisms like inflammation, oxidative stress, and even organ damage. When individuals are exposed to nano- and microplastics, they may face a plethora of severe health complications. These range from various forms of cancer to respiratory disorders that impede normal lung function, as well as inflammatory bowel disease, all of which can severely impact quality of life (Winiarska *et al.*, 2024).

8.8 Regulatory Gaps in Safety Assessment

Current regulatory frameworks are hindered by the absence of standardized protocols for the evaluation of nano-agrochemicals, which results in significant inconsistencies in safety data. One of the primary challenges faced in regulation lies in the lack of global uniformity regarding nomenclature, testing methodologies and characterization techniques. In light of emerging concerns, there is an urgent call for intensified research on micro- and nanoplastics, leveraging the findings already available in the realm of nanomaterials. Furthermore, there is an immediate need for the establishment of comprehensive standards encompassing documentary evidence, material specifications and testing methods particularly concerning micro- and nanoplastics. A thorough understanding of environmental contamination, human exposure levels and potential risks associated with small plastic particles is critical to addressing these pressing issues (Allan *et al.*, 2021).

Conclusions

Nanotechnology holds great promise for enhancing agricultural productivity, resource efficiency and precision farming. However, its implementation raises significant biosafety concerns. These include environmental impacts such as the disruption of soil microbiomes, accumulation of nanomaterials in crops and adverse impacts on species that are not the goal, including pollinators. Additionally, there are risks to human health from continuous exposure through the food supply chain, which may lead to oxidative stress and potential genetic damage. Current regulatory frameworks are often inconsistent, lacking universal safety standards for nano-agrochemicals. Existing risk assessment methods struggle to address the unique characteristics of nanomaterials, specifically their reactivity based on size and their persistence in ecosystems. While strategies like Safety by Design and lifecycle evaluations can help mitigate risks, it is crucial to enhance regulatory alignment, promote interdisciplinary research and prioritize long-term studies on ecological and health impacts. Achieving a balance between fostering innovation and implementing precautionary measures is vital for the responsible integration of nanotechnology in agriculture.

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