Chapter 8

Risks, Uncertainties, and Ethics of Nanotechnology in Agriculture

Phenny Mwaanga

Additional information is available at the end of the chapter

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Abstract

The use of agrochemicals, though has increased the agricultural productivity, has severely adversely affected soil and aquatic systems with associated flora and fauna and also the health of the farmers and society consuming the chemically grown food. Therefore, the advent of nano-agrochemicals, such as nanopesticides, nanofertilizers and nanosensors, designed to increase solubility, enhances bioavailability and promotes targeted delivery, and their controlled release will have immense potential benefits that include efficient dosage of fertilizers, improved vector and pest management, reduced chemical pollution and ultimately increased agricultural productivity. However, many questions remain unresolved on the toxicology and safety of these systems to human and ecosystems health. Risk assessment of this technology lags far behind its application. This chapter will therefore discuss the nano-ecotoxicology and risks, uncertainties, and ethical concerns of use of nanotechnology in agriculture. Furthermore, the current levels of public awareness and perception of nanotechnology will be discussed.

Keywords: nanotechnology, agriculture, nano-ecotoxicology, health risks, uncertainties, public perception, awareness

1. Introduction

The world including the developing world has seen an extraordinary growth in agricultural food crop productivity in the last 5 decades [1]. Although there are still a few reported shortages of food and incidences of hunger, particularly in few low-income countries, the reason for such food shortages is partly attributed to poor or little application of science and technology in agriculture [2]. But overall, according to some available data [1], despite the world population having more than doubled during the last 5 decades, the production of cereal crops tripled during this same period, with only a 30% increase in the cultivated land area. Thus, if the food currently produced was to be equitably distributed, there would be no person going hungry as there is more food produced than the world population needs. This increased agricultural productivity is largely attributed to the use of agrochemicals, fertilizers, and chemical pesticides [1, 3–7].

The use of fertilizers and pesticides is considered as the panacea for improved crop production [4–6]. Despite the high cost of fertilizers and pesticides, farmers are always availed with these inputs as governments in many countries provide subsidies, with a sole purpose of increasing food security. The optimal benefits from the use of these agrochemicals to a larger extent are realized, except in a few cases, particularly from some low-income countries, where farmers lack technical information such as optimum doses, correct method and right time of application. It should be understood that the requirement of fertilizers and pesticides for crops differs according to soil types and meteorology [7], and where this understanding is not followed, the increase in the use of fertilizers and pesticides may not necessarily correspond to the increased crop productivity [2], and this may be exacerbated by inability to embrace science and technology and the sole dependency on rain-fed agriculture, particularly in sub-Saharan Africa (SSA) region, where rainfall is usually erratic [5]. Elsewhere [7] huge quantities of these agrochemicals are applied to the fields under the adage that "more is better" without necessarily taking into account the soil, meteorology and other factors.

While fertilizers help in adding the nutrients into the soils required for optimal crop growth, excessive and repeated use of fertilizers can result into serious pollution. In some cases, particularly in low-income countries, the application of chemical fertilizers is done without regard to appropriate doses [2]. World over, there are many places where chemical fertilizers have left a legacy of serious pollution particularly for aquatic systems. For instance in Thailand, in Nakhon Pathom Province, in a survey conducted by some Thai scientists to determine the nitrate levels, it was found that 46% of tested ground water had elevated levels of nitrate above the WHO drinking water safety limit of 50 mg/L NO_3^- and this was attributed to agricultural activities [3]. Similarly, in rural settings of Andhra Pradesh, India, as much as 50–70% of the water resources are polluted due to contamination from agricultural activities [8]. To a large extent, this contamination results from applied synthetic nitrogen fertilizers that are unutilized by crops, which in some cases may be as much as 95% [8]. Water pollution, both for surface and ground water, from chemical fertilizers has been reported to affect many countries, including those from the European Union and other developed countries [9], and therefore, mitigation efforts require not only an integrated approach, but also a paradigm shift.

Similarly, pesticide pollution from agricultural activities is quite extensive. It is estimated that about 2.5 million tonnes of chemical pesticides are used on agricultural crops each year [10]. The repeated use of pesticides unfortunately increases pest resistance, and it is this resistance that leads to progressive increase in the amount of the applied pesticides, and sometimes this can impact the food quality. The overuse of pesticides, particularly in low-income countries, due to low literacy levels, can increase agricultural cost and generate considerable waste and pollution, which ultimately adversely affects human health and the environment. The extent of this pollution is evidenced by the pesticide residues that have been detected and quantified in a variety

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of common foods and beverages, including for instance, animal products, water, wine, fruits, vegetables and animal feeds [7, 11]. Many chemical pesticides have been associated with human health and environmental adverse effects [11]. For instance, some specific adverse human health effects associated with chemical pesticides include among others, dermatological, neurological, teratogenic, clastogenic, carcinogenic, respiratory, reproductive and endocrine effects [5, 7, 11]. The incidences of adverse human health effects from chemical pesticides are disproportionally much more prevalent in developing than in developed countries, where the majority of users have low literacy levels [5]. Ironically, while pesticides have drastically reduced agricultural crop losses, both for preharvest and postharvest, their residue levels in food stuffs, soils, flora and fauna, and water has escalated, thereby posing great risks to the farmers and consumers, including some organisms that are far removed from agricultural sites.

The continued use of these agrochemicals has led to increased levels of pollution and contamination of both aquatic and terrestrial systems with attendant adverse effects on biota. Solving these problems requires an integrated approach and a complete paradigm shift. Thus, not only the development of new and less toxic agrochemicals is necessary and urgent, but also safe, smart and efficient application methods are essential for preventing accumulation and ultimately the adverse effects on the environment. In this vain, nanotechnology offers great promise and can be used as an innovative tool for delivering agrochemicals smartly and safely [10]. Therefore, the advent of nano-agrochemicals, such as nanopesticides, nanofertilizers and nanosensors, designed to increase solubility, enhance bioavailability, promote targeted delivery and controlled release will have immense potential benefits that include efficient dosage of fertilizers, improved vector and pest management, reduced chemical pollution and ultimately increased agricultural productivity. However, many questions remain unresolved on the toxicology and safety of these systems to human and ecosystems health. Currently, the development of this technology (nanotechnology) for use in agriculture has outpaced the risk assessment, thereby posing great challenges on its acceptability by the general public and ultimately may negatively impact on the potential investment by the agricultural industry. This chapter will, therefore, contain discussions on the nano-ecotoxicology and risks, uncertainties and ethical concerns of use of nanotechnology in agriculture. Furthermore, this chapter will review the current levels of public awareness and perception of nanotechnology in agriculture.

2. Nano-ecotoxicology and risks

2.1. Nanotechnology and nanoparticles

A review of literature reveals a multitude of definitions for nanoparticles (NPs) or nanomaterials. In this chapter, a nanoparticle is defined as any intentionally produced particle that has a characteristic dimension from 1 to 100 nm and has properties that are different from that of non-nanoscale particle with the same chemical composition [12, 13]. It is well known that nanoparticles (NPs) may be naturally occurring or intentionally produced. Naturally occurring NPs result from natural processes [14] and are as old as nature, while intentionally produced NPs are often referred to as engineered nanoparticles (ENPs) and are manufactured either by the top-down approach or bottom-up approach [15]. Nanotechnology, therefore, can be defined as the design, characterization, production and application of structures, devices and systems by controlling shape and size at a nanometer scale [14]. Thus, the incorporation of nanoparticles/nanomaterials in the production of goods for application in various fields such as medicine, information and communication technology, engineering, environmental remediation, among others falls within the wider domain of nanotechnology.

NPs, due to their small sizes, have increased relative surface area and the quantum effects that have been observed to dominate the behavior of matter at the nanoscale. It is these factors that can change or enhance properties, such as strength, chemical, biological, electronic, rheological, magnetic, optical (photon), mechanical and structural, and reactivity characteristics [12, 16]. Some researchers [12] have argued that the occurrence of the novel size-dependent properties, rather than particle size, should be the primary criterion when considering the regulation of NPs for environmental, health and safety reasons. Thus, the fact that the particles or materials fit within the definition of a nano may not necessarily exhibit the "nanoness," that is, the occurrence of the novel size-dependent properties, and the size at which this nanoness is observed may be different for different materials. There are several implications of this observation in the regulation of NPs for human and environmental impacts. The first one is that the risk assessment of NPs will have to take into account the size for each material at which the nanoness is observed. Secondly, any material at nanoness, including biological NPs, can potentially cause adverse effects. Thirdly, there is a need for proper NP characterization prior to risk assessment if the risk assessment data are to be comparable. Finally, because at nanoness there is a dramatic increase in surface reactivity, most NPs tend to have increased solubility and this can pose a challenge in delineating toxic effects due to NPs from that due to dissolved ions. This last point is particularly applicable for inorganic-based NPs.

2.2. Nano-ecotoxicology and risks

The "nanoness" properties of NPs, the surface structure and reactivity are responsible for processes such as dissolution, redox reactions and the generation of reactive oxygen species (ROS) [14, 15, 17]. These are the properties that can lead to biological/toxicological effects that would not be produced by bulk particles of the same chemical composition.

Whether or not a given nanoparticle/nanomaterial will induce ecotoxicological effects on an organism upon contact, ingestion or inhalation will depend to a larger extent on its "nanoness." As argued elsewhere [12], most ENPs are likely to be of human or environmental health concern owing to their unique properties only when they have diameters of 30 nm or less. In assessing the potential adverse effects and hence the risks NPs pose to human health, a number of toxicity tests have been conducted in various media and using a variety of organisms. Literature is replete with studies that have been conducted both in vitro and in vivo, although with some conflicting results, even with the same organism for the same type of NPs. One of the possible explanations for the conflicting results would be either due to nonadherence to NP characterization requirements prior to toxicity testing or lack of NP risk assessment guidelines or both. In order to reduce such dichotomy in toxicity results, researchers have tried to understand the best dose metrics that would define the toxicology of the NPs. For instance, researchers have investigated whether a given NP type induces its toxicity through its particle charge, number concentration, mass concentration, total surface area or simply by size. Knowledge of dose metrics responsible for toxic effects as stated by some researchers [18, 19] can have a number of advantages that include easy of adaptation of the risk assessment data into the regulatory framework that ensure the safe use of such NPs, particularly in agriculture, easy of comparison of study results and hence enable regulators to formulate health-based limit values for each metric. And finally, this can also help risk assessors to compare and combine exposure and hazard information and conclude on the likelihood of health risks of each NP type.

In nano-ecotoxicology and risk assessment, various types of NPs such as carbon-, inorganic- and organic-based NPs have been investigated. This is because these types of NPs have found wide application in various fields, particularly in agriculture. Although the application of NPs in agriculture is still largely in the developing stage, there is a great potential to cover the whole food chain from production to processing, preservation, safety, packaging, transportation, storage and delivery. For instance, a variety of products exists such as nanopesticides, nanosized fertilizers, nanopromoters for plant growth, nanosensors, among others [19], which when applied cannot only come into contact with humans, but can actually be consumed along with the agricultural products. Due to their great potential to enter into the human systemic circulation system and interact with vital organs, carefully designed and comprehensive toxicity tests involving in vivo and in vitro have been carried out to assure safety to the human and environmental health.

Carbon-based NPs or carbon nanomaterials are a class of engineered nanomaterial with increased applications due to their exceptional optical, electrical, mechanical, and thermal properties. The individual NPs in this class include fullerenes, carbon dots, carbon nanotubes (CNTs), carbon nanobeads, carbon nanodiamonds, carbon nanofoils, carbon nanofoams, carbon nanofibers and graphenes [20]. Most of the carbon-based NPs have found wide application in agriculture, particularly as plant growth promoters and nanopesticides. For instance, due to their ability to effectively penetrate the seed coat and other plant tissues, carbon nanotubes (CNTs) have been used as plant growth stimulators [21]. The CNTs, single-walled carbon nanotubes (SWCNTs), have been shown to activate seed germination of corn, rice, switchgrass and tomato and enhanced the growth of different organs of corn, tomato, rice and soybean [22]. Similarly due to their superior electrical properties, CNTs have been extensively used for the development of biosensors. Thus, the NPs are usually functionalized or used in conjunction with other materials to minimize aggregation and enhance their usability. For instance, as reported in [21–23], surface functionalized CNTs were tailored with amino groups to control the efficient immobilization of acetylcholinesterase (AChE) onto the surface of glassy carbon electrode and enabled the construction of a highly sensitive organophosphorus pesticide biosensor in food stuffs where such pesticides were applied. In a bid to replace the agrochemicals, fertilizers and pesticides, carbon-based NPs have been used in the development of nanosystems for slow and controlled release of pesticides and fertilizers. As reported by [24], carbon nanofibers are used for making nanoparticles that contain pesticides and fertilizers specifically formulated to control their release into the seeds during germination.

Due to great potential for application in areas where these NPs can come into direct contact with humans, as shown above, the carbon-based NPs have comprehensively been studied on their toxicological impacts. The investigations into their toxicological effects, both for in vitro (on cell cultures) and in vivo (on organisms), have been conducted. Generally, these NPs have been observed to show some low or no toxicity in some cases [25], but in some other cases, however, the toxicity results have shown adverse effects. For instances, some studies conducted by Ostiguy et al. and Tao et al. (see [26, 27]) on some organisms using fullerenes, carbon nanotubes (single-walled or multiwalled) and nanofibers, have reported adverse effects. Similarly, a number of carbon-based NPs have also been shown to be cytotoxic to human alveolar epithelial (A549) cells, hepatocytes (Hep G2 cells), human embryonic kidney cells (HCT 116), and intestinal (P407 cells) cells [28]. Interestingly, while some studies conducted to investigate the effect of fullerenes and CNTs on plants have shown positive effects in terms of enhancing the plant growth and therefore could be commercialized as nanosystems for plant growth promoters; in other cases, a number of studies have shown that these NPs can have negative effects such as inhibitory effects against plant growth and against some beneficial microfauna [21]. Therefore to ensure that these NPs are safely used in a manner that human and environment health is ascertained, extensive and comprehensive risk assessments that include techniques that can capture delayed toxicity are required.

Inorganic-based NPs are probably the most diverse class of nanomaterials. NPs in this class include metals, metal oxide and quantum dots (QDs). They have unique chemical, physical, optical and quantum characteristics, and as a result, they have wide application in various fields such as medicines, engineering, environment and agriculture. In agriculture, as already stated, the use of huge amounts of pesticides and fertilizers results into serious environmental pollution with attendant adverse effects to humans, and sometimes, these agrochemicals affect the taste and nutritional quality of food crops. The advent of nanotechnology promises smart and intelligent nanosystems that can deliver the required nutrients to plants and nanoencapsulated slow release of fertilizers and pesticides that can deposit right doses at controlled rates. There are also nanosystems used as biosensors for detecting the presence of pesticides in agricultural products, which make use of inorganic NPs. While a lot of research is ongoing for development of such systems, already quite a few such systems are in use. For example, agribusiness and food corporations such as Monsanto, Syngenta, Kraft and BSF have already produced pesticides encapsulated with NPs [29]. Already NPs such as TiO_2, ZnO, MgO and a combination of other inorganic-based NPs, after being functionalized, have been utilized as effective nanopesticides [29]. The nanofertilizers are known to contain nanozinc, silica, iron and titanium dioxide, zinc cadmium selenide/zinc sulfide core shell QDs, indium phosphorus/zinc sulfide core shell QDs, manganese/zinc selenide QDs, gold nanorods, core shell QDs, specifically designed to control release [30]. Other inorganic NPs have been used as plant growth promoters, nanobiosensors among others. As reported by [23], ZnO NPs have been used as nanofertilizers and enhancement of nutrient absorption for plant growth. Within the wide context of agriculture, the quantum dots due to their characteristical electric and optical properties have been used as nanosensors and nanobiosensors. For instance, as reported by [31], cadmium selenide (CdTe) has been used as pesticide nanosensors for detection of 2,4-dichlorophenoxyacetic acid in food crops.

Because their application, particularly in agriculture, was envisaged to involve direct interaction with human biology and physiological systems through ingestion, these NPs have been widely investigated on their potential adverse effects. Toxicity of NPs and inorganic NPs in particular is well established. Literature is replete with cases where the inorganic-based NPs have been shown to cause both acute and chronic toxicity. The toxic effects have been observed in plants, animals, microflora and microfauna including cell lines. However, as observed by [32], most of the available data on ecotoxicology are limited to species used for regulatory purposes. That is, although the ecotoxicological data are available for aquatic and terrestrial organisms, it is predominantly from species deemed highly sensitive. For the purposes of understanding the toxicity potential of these NPs, these data are adequate. For cute toxicity, NPs such as Cu, CuO, Se, Zn and ZnO, and TiO_2 have been implicated in numerous studies [18]. For instance, silver and copper NPs were observed to cause adverse effects to both zebra fish and *Daphnia pulex* [33], while Cu NPs were observed to cause oxidative stress to earthworms, *Eisenia fetida* [34]. Commonly encountered metal oxide NPs such as CuO, ZnO TiO_2, SnO_2, CeO_2 and Fe_2O_3 have also been implicated in causing diverse adverse effects to organisms [28, 32, 34]. In terms of their use in agriculture, the long term or chronic effects of these NPs are of paramount importance. As reported elsewhere [35, 36], the quantum dots, metal and metal oxide NPs have been implicated in the long-term effects. Quantum dots are particularly toxic as they are usually made from already known toxic materials. For instance, cadmium-selenide (CdSe), cadmium-telluride (CdTe), selenide/zinc selenide (Se/Zn Se) and gallium (Ga) have been shown to cause immunotoxicity, oxidative stress and DNA damage [37, 38]. In most cases, the inorganic-based NPs are coated or encapsulated immediately after synthesis to prevent any aggregation and preserve their properties. Usually this surface functionalization can result into behavioral modifications, which in turn have a direct impact on their surface charge, size and reactivity. This then may be followed by a reduced toxicity.

The use of organic-based or polymeric/dendrimeric NPs in agriculture is equally wide spread. These NPs can be synthesized as nanowires or nanofibers and may be designed as hydrophilic or hydrophobic depending on the anticipated application. These NPs have useful characteristics that include biocompatibility and biodegradability, which confer upon them a multiplicity of application in various areas including agriculture. Examples of organic-based NPs include liposomes, vesicles, and micelles, dendrimers, nanocapsules and polymeric NPs. Like other classes of NPs, the organic NPs have equally been used in the formulations of smart-delivery nanosystems. For instance, the encapsulation of pesticides in the organic NPs ensures that there is slow and controlled release of the active ingredient, and therefore delivering more effective control over certain pests at lower dosage rates and over a prolonged period of time [39]. This reduces the overdosing and hence prevents pollution. Moreover, as smart systems, the nanopesticides are designed to increase the dispersion and wettability of agricultural formulations and unwanted pesticide movement. The nanopesticides have increased solubility and therefore can reduce contact of active ingredients with operators in the fields, thereby reducing the incidences of accidental toxic effects. Furthermore, these organic-based nanopesticides have the advantage of being biodegradable and therefore get assimilated into the soils, thereby adding some additional nutrients. Currently, there are quite a number of commercially available pesticides encapsulated by organic NPs. For example, [40], bifenthrin nanopesticide used for protection of agricultural crops has been formulated using polymers such as poly (acrylic acid)-b-poly (butylacrylate) (PAA-b-PBA), polyvinylpyrrolidone (PVP), and polyvinyl alcohol (PVOH). Similarly, fertilizers encapsulated with the organic-based NPs are commercially available and some of the commonly used organic materials include chitosan, nanocapsules (liposomes), polyethylene glycol (PEG), starch, cellulose, Poly(d, l-lactide co-glycolide) (PLGA) and polyester substances. Other smart nanosystems such as nanobiosensors for the detection of pesticides in food crop have been developed from the organic-based NPs.

As a result of envisaged wide application, the toxicological aspects of these NPs have been investigated. While some of the NPs have low or no established toxicity, some have been found to induce some toxic effects. For instance, polymeric, polyethylene glycol (PEG) NPs, Poly(d, l-lactide co-glycolide) (PLGA) NPs and solid lipid nanoparticles can cause immunotoxicity, nephrotoxicity and lung toxicity, respectively [41]. Similarly, some dendrimeric NPs such as polyamidoamine and poly (propyleneimine) have been investigated for their possible toxicity both in vitro and in vivo, and have been shown to have some concentration-based toxicity [42].

In general, the projected increase in the production and commercialization of NPs due to their novel properties will eventually lead to their increase in the environment with attendant increase in the exposure to organisms and hence with the concomitant adverse effects. But in terms of their use in agriculture, the kind of impact and adverse effects NPs may cause has probably not yet been clearly elucidated by the current risk assessment methods. A quick survey of literature shows that there has been an extensive evaluation of the toxic effects of NPs and currently these evaluations are still ongoing. It has been shown that most NPs exhibit some toxic effects, though in a number of cases conflicting results have been observed. There are numerous mechanisms by which different NPs induce their toxic effects, and these include cell proliferation, necrosis, apoptosis, DNA damage and oxidative stress among others. Interestingly, however, these same mechanisms have also been shown to be caused by environmental toxicants such as metal ions, pesticides, PCBs and other industrial chemicals [43, 44]. Thus, in investigating the minimal concentrations of NPs that can cause adverse effects, particularly in the actual environment that contain other toxicants, the risk assessment should involve aspects such as additivity, synergistic, potentiation and antagonistic effects. This kind of information is hugely beneficial in terms coming up with the regulatory framework and policies aimed at protecting human health with regard to nanotechnology in agriculture. This is because besides humans being exposed to NPs through nanotechnologically grown foods, they (humans) are also exposed to various other industrial chemicals through ingestion, inhalation and dermal contact. It is of no doubt, however, that the current assessment of the risks posed by NPs has a number of inherent limitations and uncertainties. The degree of uncertainty to a large extent is dependent on the application to which the NPs will be subjected.

3. Uncertainties of nanotechnology in agriculture

There is no doubt about the potential applications and benefits of nanotechnology in agriculture. In fact as research into the use of nanotechnology in agriculture matures, many more nanoproducts and nanosystems will be developed and commercialized to the benefit of the whole agricultural value chain. As observed earlier, the general risk in the application of nanotechnology in various fields has been reasonably assessed. In agriculture, however, the current risk assessment data do not seem to be sufficient for both industry and consumers to make informed choices about the use of this technology. This insufficiency of data leads to some significant uncertainties that relate to consumer and environmental safety, which is critical in the regulatory framework, and a necessary ingredient in giving public confidence in the products. In addressing the current state of uncertainties, there are a number of critical questions that need to be answered. For example, is current toxicity testing protocols sufficient to provide necessary information on delayed toxicity of NPs? Which dose metric best describes the toxicology of NPs, particularly through those that gain entry into humans through ingestion? Are there currently some validated techniques and methods that can detect the presence of NPs in the food matrix? Is there sufficient regulatory framework to ensure safety of NPs related to their use in agriculture? Is the NPs toxicity data from cell lines sufficient to inform regulatory framework? Are there some guidelines on the generation of NPs risk assessment data to ensure comparability of such data? Are risk assessment protocols used for both aquatic and terrestrial organisms sufficient to provide credible information for the exposure of humans through ingestion? What impacts will these nanosystems have on beneficial soil microorganisms? And finally, to what extent do these NPs accumulate and biotransform in plants? These and several other questions will be dealt with in this section as the issue of uncertainty in nanotechnology in agriculture is being discussed.

The question of whether the current toxicity testing protocols are sufficient to provide necessary information on delayed toxicity of NPs is one that speaks to the adequacy/inadequacy of the design of the risk assessments. The majority of the data from risk assessments is from traditional toxicity tests that rely predominantly on mortality and sublethal endpoints such as oral, dermal and ocular toxicity; immunotoxicity; genotoxicity; reproductive and developmental toxicity; teratogenotoxicity; carcinogenicity, growth, foraging, behavioral changes and among others. These toxicity tests are quite costly and time consuming [45]. Unfortunately, most of these tests do not necessarily capture the delayed toxicity and these do not give an opportunity for reliable prognosis about the ultimate effect on organisms. There is a suggestion that in order to understand the long-term impact that some of the NPs used in agrochemicals may have on human health and environment, more studies should begin to incorporate the genomics and proteomics techniques. These techniques though they involve the state of the art of instrumentation can prove to be faster and cost effective in the long term, particularly in the face of thousands of nanochemicals that are anticipated to be generated in the coming decades.

The aspect of the dose metric that best describes the toxicology of NPs, particularly, has been the subjective of debate among nano-ecotoxicologists for quite some time. Traditionally, mass has been used a dose metrics for most risk assessments for most NPs. However, other dose metrics such as surface area, number of particles, volume and size have also been investigated on their influence on toxicity, irrespective of chemical composition [46]. While in some cases, a particular dose metric could be responsible for the observed toxic effect, in other cases, another dose metric may be responsible. This creates some uncertainty, and thus, risks assessments for NPs need to ensure that all factors of a given NP type that lead to some toxic effects are clearly understood. This is particularly important because NPs have different characteristics. Thus, some NPs are soluble, while others are insoluble and further still some may be biopersistent.

Some uncertainty arises from lack of validated techniques and methods that can detect the presence of NPs in the food matrix. The detection and ultimate characterization of different types of NPs in agricultural food is necessary in understanding the benefits as well as the potential risks. Although some (few) methods for detection and characterization of such NPs are currently available, these methods need to be validated in addition to the need for the development of standard materials required in such methods [47]. Given that there are a number of NPs that are being developed for use in agriculture, need exists for research and development of more and validated methods required in the detection of NPs in agricultural products, especially food crops.

Although many countries are now setting definitions and regulatory frameworks for nanotechnology, the very nature of NPs in many ways makes it quite challenging in coming up with separate legislation that deals with these miniature materials away from their bulk counter parts. For example, as reported elsewhere [48], both the United States Food and Drug Administration (US FDA) and the United States Environmental Protection Agency (US EPA) have not recognized nanomaterials as the new chemicals and that nanomaterials do not require any new oversight. Ironically, these bodies (especially US FDA) require manufacturers of food products to demonstrate that the food ingredients and food products are not harmful to health; yet, as already stated, there is no regulation that specifically covers nanoparticles, which could become harmful only in nanosized applications. In the similar fashion, it is interesting to note that the European Union's main regulation covering nanotechnology applications is the REACH (EU Regulation on Registration, Evaluation, Authorization and Restriction of Chemicals) [23]. Generally, because nanotechnology is relatively new, at the global scale, there are currently no clear regulations governing the production, use, labeling and disposal of NPs/nanomaterials [21]. With the predicted increase in the production and commercialization of nanosystems for use in agriculture, there is a need for clear cut legislation and policies to protect and foster public health and confidence.

As already pointed out, the majority of the risk assessment data is from traditional in vivo animals tests. In as much as these tests can yield some useful information necessary to inform the regulatory framework, they are costly and time consuming. Additionally, the traditional tests normally involve one type of NPs at time. But humans will be exposed to these NPs used in agriculture together with other chemical contaminants. The data from these tests therefore may have an inherent degree of uncertainty. Recently, there has been some suggestion for using genomics, proteomic, transcriptomics, and metabolomics (the omics techniques) as high-throughput techniques, utilizing cell lines to cope with the rate of the production of the nanomaterials. Here again, there would be quite a number of uncertainties. For example, how reliable is the data from such techniques in terms of extrapolatability and predictability to human biology and physiology? Particularly, what is the degree of uncertainty for these data obtained from isolated cell lines kept in culture medium without the benefit of cross talk and interaction from other organs, as would be the case in the in vivo tests, have? The protective regulatory framework should always take into account the uncertainty to assure public confidence and trust.

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There are quite a number of reasons why application of nanotechnology in the agriculture is still relatively at an infancy stage in comparison with other fields. The major ones include potential consumer health risks and a lack of unifying regulations and guidelines on risk assessment of nanotechnology. The use of nanotechnology in agriculture more than any application can lead to the introduction of NPs/nanomaterials into the human biology and physiology. Therefore, when risk assessment is not guided by unifying guidelines and regulations, then the risk quotient may be high and this can make the technology nonattractive to industry and consumers alike. In trying to harmonize the NP risk assessment data and ensure comparability, there is need for some guidelines on the generation of these data. Currently, one of the challenges relating to the usability of NP risk assessment data in regulatory framework is the somewhat conflicting nature of the toxicity results by different researchers. When there are specific guidelines to follow during the processes of conducting risk assessment of nanomaterials/NPs, the degree of uncertainty is minimized and regulatory framework can easily be formulated, particularly for a field such as agriculture.

Risk assessment protocols used for both aquatic and terrestrial organisms have contributed greatly in understanding the effect of NPs to organisms and to a large extent have provided credible information required for the development of safety guidelines on nanotechnology in general. However, with regard to application of nanotechnology to sensitive fields such as medicine and agriculture, new protocols and research designs of evaluating safety of NPs are required. For instances, are doses used in the actual environment, be aquatic or terrestrial, with a milieu of environmental matrices useful in extrapolating the effect to humans? And what is the contribution of other environmental toxicants to the observed toxic effects of NPs? These and several other questions need to be investigated in order to ensure nanotechnology safety in agriculture.

In addition to safeguarding human health as benefits of nanotechnology in agriculture increase, the safety of beneficial soil microorganisms which enable nutrient cycling and hence help to maintain basic soil fertility, need to be protected. Thus, there is need to carry out comprehensive NP risk assessment for all the NP types envisaged to be used in agriculture. And finally, more work needs to be done in investigating whether or not NPs can bioaccumulate and biotransform in plant materials.

4. Ethical concerns, public awareness and perceptions

Although nanotechnology is viewed as one of the key technologies of the twenty-first century and has major potential benefits, it has to be embraced with a precautionary measure, given that not much is known about its unintended effects on account of being new. Despite there being a lot of applications for nanotechnology in many fields and increasingly more applications are being employed in the field of agriculture, the general global population seems to know little about nanotechnology. Interestingly, however, as reported by [16, 49], a large proportion of the US and the European public have equally very limited knowledge about nanotechnology. These researchers concluded that despite the US public possessing little knowledge, a majority believed that benefits of nanotechnology outweigh the risks as compared with the majority of the European public who viewed nanotechnology with less optimism. It should be quite obvious that if public knowledge of nanotechnology in such highly advanced societies where literacy levels are relatively high is limited, then the situation is worse in other parts of world that are also grappling with high illiteracy levels. As expected, the level of knowledge of nanotechnology is much higher among the highly educated than those with least education.

When people know little about a technology, their perception and acceptability will to a large extent depend on how social and ethical issues concerning the technology are handled by industry and researchers. As stressed by [49], when knowledge is missing, people can use heuristics, such as trust, to assess the risks and benefits of a new technology. Thus, people are more likely to accept assurances about the safety of nanotechnologies, including nanotechnology in agriculture when they have higher levels of trust in the institutions, researchers and industry, emanating particularly legislative history. Another aspect that affects public perception about nanotechnology is the way the media reports issues on the technology. In less developed countries, the level of coverage of nanotechnology is very low and this is coupled with low levels of research in the technology. For developed countries with high levels of application of nanotechnology, the reporting or coverage of nanotechnology may be modest probably due to the specialized nature of the field and hence requiring specialist journalists who may be fewer [50].

Based on the factors that influences the perception and awareness of the nanotechnology in agriculture, there are quite a number of ethical issues that arise. In the face of the potential risks that nanotechnology in agriculture pose to human health and environment, should the industry continue using these nanosystems despite the uncertainty? Should there be a mandatory requirement for labeling of nanoenabled agricultural products, particularly food stuffs? Is it ethical that public/government institutions should continue funding development of nanotechnology products for use in agriculture despite the current levels of uncertainty? How much information should the public be made aware in relation to the nanotechnology in the whole agricultural value chain? Is it ethical for an industry to release nanosystems for use in agriculture to the public who have no idea about the potential negative impact on their health? Should there be regulations set in regulating nanotechnology in agriculture to increase public perception and acceptability? If these issues/questions are not fully addressed while the nanotechnology in agriculture is still in the development stage, the negative perception and hence reluctance of acceptance of this technology, similar to what was witnessed to genetically modified (GM) food stuffs, particularly in the European Union region may be experienced again.

5. Conclusions

There is no doubt that agrochemicals, fertilizers and pesticides have contributed greatly to the growth and increase in agricultural production. As observed, the last five decades has witnessed unprecedented increase in food production with only a marginal increase in cultivated land area. Despite huge benefits in terms increased agricultural productivity due to the agrochemicals, the excessive use of these chemicals has resulted into serious pollution to aquatic and terrestrial systems. The pollution has also resulted into increased disease burden, particularly to humans, as a result of consuming food and eaters contaminated with agrochemicals. The residues of pesticides have been detected and quantified in most agricultural food crops, while elevated levels of nitrates from chemical fertilizers have been found in both surface and ground water resources in various places across countries and continents. One of the main reasons for agrochemical pollution is due to yearly progressive increase in their application. For fertilizers, in some cases, only a small fraction of what is applied get utilized by plants. Therefore, the advent of smart nanosystems such as nanopesticides, nanofertilizers and nanobiosensors, among others, designed to increase solubility, enhances bioavailability and promotes targeted delivery and controlled release over a long period of time will immensely benefit the whole agricultural value chain. Thus, nanotechnology in agriculture will improve the efficient dosage of fertilizers, improve vector and pest management, reduce chemical pollution and ultimately decrease contact with agricultural operators.

The development of smart agrochemicals and other nanosystems for use in agriculture is still in the developmental stage. Of course currently, there smart nanopesticides, nanofertilizers and nanobiosensors that are in use and have made a huge impact in revolutionizing agriculture. However, the use of nanotechnology in agriculture has a number of risks, uncertainties and ethical concerns from the public perspectives. Different types of NPs that can potentially be used in the design and production of nano-agrosystems have been assessed in terms of their risk to human and environmental health. NPs from different NP classes such as carbon, inorganic and organic based have been subjected to safety evaluation. Interesting and useful data have been generated. However, the adequacy of the risk assessment for different NPs intended for use in agriculture remains an open question. Several issues have been raised about the sufficiency of the current risk assessment data for the formulation of protective legislation to human health from nanotechnology application in agriculture. Questions such as: are current toxicity testing protocols sufficient to provide necessary information on delayed toxicity of NPs? Which dose metric best describes the toxicology of NPs, particularly through those that gain entry into humans through ingestion? Are there currently some validated techniques and methods that can detect the presence of NPs in the food matrix? Is there sufficient regulatory framework to ensure safety of NPs related to their use in agriculture? Is the NPs toxicity data from cell lines sufficient to inform regulatory framework? Are there some guidelines on the generation of NP risk assessment data to ensure comparability of such data? Are risk assessment protocols used for both aquatic and terrestrial organisms sufficient to provide credible information for the exposure of humans through ingestion? What impacts will these nanosystems have on beneficial soil microorganisms? And finally, to what extent do these NPs accumulate and biotransform upon entry into plants? All these questions demand new approaches and perspectives in the design of risk assessment methods to ensure that humans and the environment are safeguarded from NPs potential harm as a result of their application in agriculture.

Other issues of concern that have been discussed about nanotechnology include low or limited knowledge of the general public about nanotechnology and low levels of publicity. Despite numerous benefits of any technology, when that technology is unknown, people will only resort to using heuristics such as trust to inform their perception about risks and benefits. If industry and the public regulators, for instance, FDA, have built a good relationship with the general public in terms providing good oversight, through trustworthy information, the public is inclined to believe when assured that a given product is safe. Furthermore, some ethical issues arise as to how much information the general public is given on the potential risks of the nanotechnology in agriculture. The role of the media is critical in shaping public opinion and perception about a given technology. Unfortunately, only few journalists are well schooled to report appropriately and effectively on issues of nanotechnology in agriculture. In order to gain public acceptance and avoid incidences of negative connotation of this new technology, similar to what was witnessed to genetically modified (GM) food stuffs, particularly in the European Union region, there should be adequate follow of information. The labeling of agricultural crops containing NPs should be encouraged to promote the free choice of use of such products by the public.

Author details

Phenny Mwaanga

Address all correspondence to: phennym@yahoo.co.uk

Department of Environmental Engineering, Copperbelt University, Kitwe, Zambia

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