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Toxicological And Ecological Perspectives On Nanomaterials: A Comparative Review

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Nanotechnology has been described as among the most radical scientific fields of the twenty-first century, promising uses in medicine, agriculture, consumer products, and environmental cleanup. The focus of this new novelty is nanomaterials, which due to their physicochemical properties are dictated by their nanoscale size, high surface area, and reactivity and can exhibit a functionality never previously observed, but with serious toxicological and ecological potential. This review is a critical comparison of the two antagonistic nanotoxicological and ecotoxicological issues in order to provide a composite opinion on the ecological and health risks associated with nanomaterials. In the case of toxicological point of view, nanoparticles have been shown to penetrate barriers to biology, localize in body organs and induce oxidative stress, damage DNA, inflammation and carcinogenicity potential. Human routes of exposure by way of inhalation, ingestion, dermal absorption, and of the greatest importance are medical and occupational and consumer safety. Nanomaterials enter the environment as manufacturing, use and disposal and impact the soil fertility, aquatic ecosystems, biodiversity and food chain through bioaccumulation and biomagnification. Similar action mechanisms such as oxidative stress and bioaccumulation are reported to take place at cellular, but also at an ecosystem level, yet toxicological studies are performed at an individual cell, and ecological studies at the stability of the population and ecosystem. Human and environmental health dependence shows the relevance of a One Health approach where molecular and ecological as well as regulatory perspectives are included. Regardless of the increasing evidence, there is knowledge gap especially in long-term exposures at low doses and exposures dynamics in practice. The paper concludes with the recommendation that nanospecific regulations, green nanomaterial design, interdisciplinary research and sustainable innovation need to be integrated in order to balance the positive and the potentially risky aspects of nanotechnology. This review will find application in the framework of the holistic risk assessment systems required to safeguard human health, environmental sustainability, and sustainable industrial growth by synthesis of toxicological and ecological evidence.

Keywords: Nanotechnology, Nanomaterials, Nanotoxicology, Ecotoxicology, Oxidative Stress, Bioaccumulation, Human Health, Environmental Safety, One Health, Sustainable Innovation.

1. Introduction

1.1 Background to Nanomaterials

Nanotechnology is indeed emerging as one of the most radical scientific and technological fields in the twenty first century. In simple terms it can be defined as the working and manipulation of materials within the nanometer scale i.e. typically 1-100 nanometers. This size range of engineered materials possesses novel chemical, physical and biological behavior compared to their bulk versions, and finds application in an ever-expanding range of ways. Nanomaterials are also finding their way into medicine, electronics, farming, environmental remediation, food packaging and energy production. These include silver nanoparticles (commonly used in commerce to impart antimicrobial properties to consumer products) and carbon nanotubes and quantum dots, which are finding numerous applications in biomedical imaging and drug delivery. Nanomaterials are turning out to be multi-purpose and also is becoming extremely dangerous in bringing about emergency regarding the safety question of nanomaterials and also the long-term effects of nanomaterials on both human health and the environment [1].

Nanomaterials have wonderful attributes but the tiny dimensions, broad surface area, and reactivity of nano-particles make them active biologically in unexpected ways. Nanomaterials penetrate biological barriers, build up in the tissue and linger in the environment more than traditional chemicals. Their locations are also of new interest to both toxicology and ecology as the conventional risk evaluation models were never designed to accommodate effects at a nanoscale. This has been a motivating factor towards raising the volume of studies targeted at the potential impact they will have on the living systems and ecosystems [2].

Among the toxicological and ecological concerns, there is the increased production, use and disposal of nanomaterials. In terms of toxicology, it has been shown through experimentation that toxicity of the organ, oxidative stress, DNA damage, inflammation, and DNA damage can be induced under the influence of a certain number of nanomaterials. It is also associated with adverse effect on occupational health, consumer health, and medical ethics since nanoparticles could find their way into the human body through inhalation, ingestion, dermal penetration or medical procedure. Instead, the ecological perspective is about the interface between nanomaterials and the environmental systems (soil, water, organisms). As we will see, nanoparticles have been found to destabilize microbial communities, impair plant growth, bioaccumulate in aquatic organisms and alter food chains. These facts contribute to the irreducible nature of the toxicological and ecological risks due to the inability to talk about human health in terms of the integrity of the ecosystem.

With or without the accrued literature, chances are that most studies will not explore ecological or toxicological effects alone. These two methods are not compared and combined in order to create the full picture of dangers of nano-materials in many reviews. As the pace of nanotechnology commercialisation accelerates, this accumulated knowledge is assuming an extremely central role as policy-makers, regulators, scientists and industries strive to realise the greatest good with the least harm [3].

In the two domains of nanotoxicology and ecotoxicology, though abundant literature can be found on the history of both, a big gap exists between gathering a list of one half of the coin. The current literature is typically highly selective and comments on individual nanomaterials, organisms or conditions in an ad hoc fashion leading to a body of disjointed data. Moreover, the results of toxicological and ecological studies and their refinements are more likely to vary, and therefore, cannot be easily compared. This is a weakness to regulators and other interested parties who expect multi-layered risk assessment that cross-cuts human and environmental health. This gap shall be addressed in the current Review Paper by undertaking a comparative review in the context of building up a synthesized knowledge of the impacts of nanomaterials on human and the environment [4].

To critically assess and compare the toxicological and ecological approaches to nanomaterials and their possible hazards to human health and the environment and gaps in future research.

2. Literature Review and Background

2.1 Nanomaterials Toxicological Impact on Human Health

As 5 shows, nanomaterials pose special problems to human health, because of their special physicochemical properties. Their nanoscale diameter of 1-100nm enables their penetration through biological barriers inaccessible to bulk material, and leads to novel routes of exposure and toxicity. Sources of entry into the human body are numerous and diverse, including by inhalation, ingestion, dermal absorption and medical procedures. Inhalation is one of the gravest problems, particularly to the people who work in the industries that manufacture or handle nanomaterials. Comparison has been drawn between asbestos fibres and carbon nanotubes (CNTs), because of their length, tubular structure, their persistence in the body, and the ability to induce pulmonary inflammation and fibrosis. The other pathway continues to ingestion, which is either accidental by consuming polluted water and food or intentional by consuming food additives (nano-particles), such as titanium dioxide nanoparticles (TiO2-NPs). In food packaging and in sunscreen TiO2-NPs are utilized and in experimental research it has been determined that with repetitive exposure, the TiO2-NPs build up in vital organs such as the spleen and liver. Dermal penetration is applicable in the consumer product (largely cosmetics) market, although the rate of absorption is determined by the nature of nanoparticles and the surface chemistry. It also presents risks of systemic circulation effects and organic toxicity (liver and kidney) when used in medicine (e.g. in the intravenous administration of dendrimers or quantum dots).

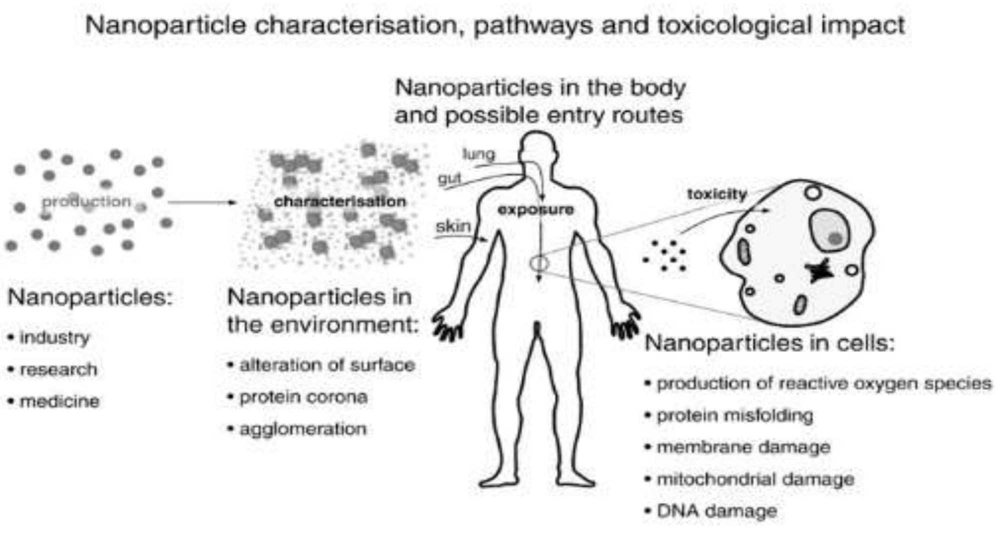

Figure 1: Nanomaterials
Source: [31]

As observed by [6], this means that Nanomaterials can be transported all around the body once they are already in, and can bypass natural defence mechanisms by translocation of entry sites at one organ to other organs. This spreading ability generates this pattern of multi-organ toxicity that is specific to traditional chemicals. Of particularly topical interest is also the pathophysiology of toxicity, to which oxidative stress has been recognized as a significant contributor. Nanoparticles can also generate reactive oxygen species (ROS), which overload antioxidant defences and lead to cellular injury, lipid peroxidation, protein denaturation and strand breakage of DNA. AgNPs like these have been linked to ROS mediated mitochondrial dysfunction and subsequent apoptosis in epithelial cells of the lungs. Near the inflammatory responses is the c stress pathway. Exposure to CNT activates alveolar macrophages, leading to cytokines release, chronic inflammation, fibrotic change and malignancy. Similarly, TiO2-NPs have been reported to cause GI inflammation and to modify the gut microbiota, implying the possibility of emerging gastrointestinal illnesses.

According to [7] the other consequences are genotoxicity and carcinogenicity. Other nanoparticles escape repair, or damage DNA, resulting in chromosome aberrations, the development of micronucleus and genomic instability. These products do suggest chronic hazards, e.g., mutagenesis and carcinogenesis. It is worth noting that organ exposures do not yield similar outcomes depending on route of exposure. The primary CNTs inhalation, TiO2-NPs ingestion and gastrointestinal toxicity, toxicity in the liver, ingestion and fibrosis of the lung, mesothelioma and intravenous medical uses are connected to the toxicity of nanomaterials to the body, kidney and liver and liver.

These observations have been of particular focus in in vivo and in vitro research. In vitro DNA fragmentation, abnormal proliferation and apoptosis of human lung cells exposed to CNTs and mitochondrial swelling and membrane disruption induced by AgNPs in epithelial cells have been reported (Soto et al., 2008) and (Wireza, 2016), respectively. There is also other in vivo experiments that have supported AgNPs by means of rat inhalation models proving that AgNPs are deposited in the lungs where it translocates to brain and liver leading to neurotoxicity and behavioural change. Mice were found to accumulate in the kidneys, and develop dysfunctional renal functions when exposed to TiO2-NPs on a series of occasions. Despite these observations, it is hard to extrapolate on human populations due to few epidemiological studies. Occupational exposure tests show that respiratory symptoms and evidence of oxidative stress increased in the workers of the nanomaterial, although no longitudinal measurements were made.

This has been critically reviewed with constraints. Many of the laboratory experiments involved in risk assessment rely on impractically large doses and cannot be compared to real-world exposure levels. Toxicity is highly sensitive to features of the particles such as size, shape, charge and coatings and generalisation is not easy. The number of long-term epidemiological studies that are able to assist in building a developed picture of chronic outcomes is extremely low. In addition, the regulatory frameworks tend to group nanomaterials by the accessible chemical hazard groupings, irrespective of nanospecific behaviour and hazards (OECD, 2021). Together, these toxicological investigations show significant risks, but also the need of more realistic exposure models, long-term research in humans and nanospecific safety guidelines.

2.2 Nanomaterial Ecological Effects on the Environmental Systems

[8] examined that Beyond the immediate human health implications, nanomaterials will inevitably enter and interact with the environmental systems at the ecological risk scale. Other important routes of contamination include the release of nanoparticles into the environment during manufacturing, use and disposal, industrial effluents, and landfill leachates. Zinc oxide nanoparticles (ZnO-NPs) in sunscreen, including leak into water and dissolve to release zinc ions that are saltwater life killers. Similarly, when AgNPs are implanted in fabrics, they amalgamate in sewage sludge; here, the sludge containing the nanoparticles transfers to soil ecosystems and affects plants and microorganisms when the sludge is then used as a fertiliser. Aggregation, dissolution, and attachment of nanomaterials to natural organic matter are some of the processes that affect the environmental fate of nanomaterials and reduce or maximize toxicity.

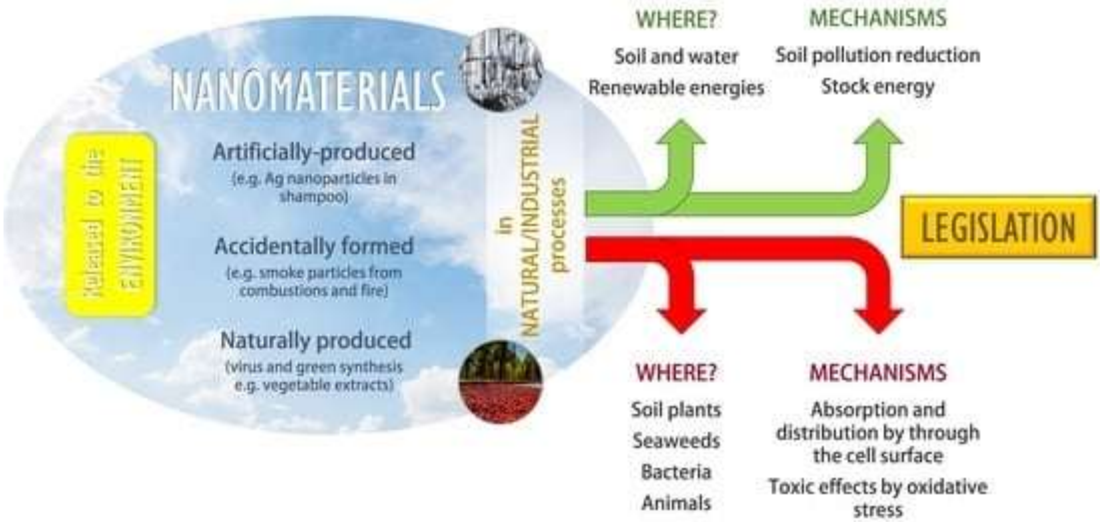

Figure 2: Environmental Impact of Nanoparticles' Application as an Emerging Technology Source: [32]

According to [9], the initial organisms to be exposed to nanomaterials in soil and aquatic niches are microorganisms. To be more specific, AgNPs are claimed to be very effective antimicrobials: they block respiratory enzymes, destroy cell membranes and disturb microbial ecosystem. The disruptive impact that are impinging on the fundamental processes such as the nitrogen repair and the long term processes such as the fertility of soils and nutrient-cycling. It also presents threats to plants by disrupting their germination, root growth and photosynthesis. As we have demonstrated, TiO2-NPs decreases the occurrence of chlorophyll and interferes with the photosynthetic ability of wheat, and ZnO-NPs slows down the development of roots in maize, leading to a decrease in its output. Nanoparticle pollution is especially dangerous to aquatic life, as the chemicals have a tendency to concentrate in sediments. Zebrafish embryos subjected to CNTs had defects including spinal defects (Cheng et al., 2007). Invertebrates (molluscs and crustaceans) bioaccumulate nanoparticles and modulate feeding behaviour and reproductive output of daphnia populations that have been contaminated with AgNPs.

According to [10], Another critical ecological concern is that bioaccumulation and biomagnification may occur. It was also observed that higher trophic levels pollute the food webs as one ascends the trophic level i.e. starting with gold nanoparticles (AuNPs) to the algae to daphnia and ultimately fish. The fact that CNTs and TiO2-NPs are not destroyed but accumulate in the sediments over time adds to this risk. Also, nanomaterials can also be vectors of other contaminants, in what is known as the Trojan horse effect. Nanoparticles will absorb heavy metals or organic compounds and transport them to organisms in large amounts that are toxic. The indicatively useful CNTs are those loaded with polycyclic aromatic hydrocarbons (PAHs) which have been shown to increase toxicity when consumed by aquatic organisms.

Ecological studies have enormous challenges though evidence is piling. Laboratory experiments are often simplified designs that do not reflect a complex real ecosystem. Lack of understanding of chronic and intergenerational effects is limited to a few research works conducted over a long period. Environmental conditions that may alter nanoparticles to alter the patterns of toxicity, but so far have not been carefully studied, are sunlight, pH and organic matter. Furthermore, the evidence is intermittent within both species and ecosystem borders, in addition to the difficulty in creating all-inclusive assessments. Nonetheless, there is unanimous agreement as far as the available literature is concerned, that nanomaterials could disrupt key ecosystem services and biodiversity and introduce potential risks which are long term as a result of persistence and bioaccumulation.

2.3 Comparative Insights: Convergence and Divergence between Toxicological and Ecological Viewpoints.

It is demonstrated in [11] that despite the tendency of toxicological and ecological studies to proceed in parallel, comparative studies suggest that the two approaches share and differ in a number of ways. The coincidence can be attributed to similar mechanisms, notably oxidative stress that has been found to be a major damage pathway to both human cells and environmental living organisms. In one of them, AgNPs inflict ROS caused cellular damage in human lung epithelial cells and bacteria (Choi and Hu, 2008) in water. Bioaccumulation is another domain of overlap; nanoparticles have been shown to accumulate in human organs (liver and brain), as well as in the environment (in plants, fish and invertebrates). The two perspectives also indicate the dearth of chronic, low dose research with the majority of studies conducted on acute, high dose exposures.

Divergences are another issue, however. Toxicological studies are generally predisposed towards both controlled laboratory studies at the cellular or organ level, and ecological studies at the population and ecosystem level. Outcomes may also be quite unpredictable; TiO2-NPs, specifically, may appear to be moderately non-toxic to mammalian cells and highly disruptive to photosynthesis in plants in the natural condition. The toxicology methodology is based on molecular and mechanistic analysis, whereas the ecology is based on environmental contacts and system responses. These silos in discipline pose barriers to integrative evaluations of risk and regulatory decision processes.

It is interesting to note that [12] indicates that environmental risks are more likely to impact on human health indirectly. Water pollution reduces the number of fishes which affect food security. Soil pollution diminishes the productivity of farms, thus threatening food security, and the microbial disturbance diminishes the functions of the ecosystem that are essential to human survival. One Health model has been put forward as a means to correct these co-morbid threats through an integrative approach to the wellbeing of man, beast, and the environment. According to this framework, cross-disciplinary approach to the study of nanomaterials has some significance.

Important gaps exist in knowledge. Few studies examine toxicological risk and ecological risk simultaneously and policymakers are given bits and pieces of evidence. There are few chronic, low-dose and field-based studies that are representative of actual real-life. Environmental changes (i.e. nanoparticle dissolution or aggregation) not well understood. The tools needed to address these complexities are rather scarce in regulatory frameworks because science evolves faster than policy. The future of observational work in this context should thus be interdisciplinary in the sense that it integrates the insights of mechanistic work, ecological models, epidemiological statistics and long-term field observations to produce holistic risk assessment.

Ecological research is less complete than toxicological research and finance is less available to toxicological research, but toxicological research has provided useful mechanistic information in critical review. Integrative frameworks, such as One Health are underutilised and offer a good path forward in terms of harmonising perspectives and improving regulation. Without more cross-disciplinary work, nanotechnology innovation will continue to be ahead of regulation, which has subjected human and ecological health to unrecognised risk.

Annotation

Year	**Author(s)**	**Key Findings**	**Reference**
2024	Qamar et al.	Highlighted multiple toxicological effects of nanomaterials on human health, including oxidative stress, DNA damage, and organ toxicity.	[5] Qamar W, et al. (2024). *PeerJ*, 12:e17807.
2022	Rolo et al.	Systematic review on TiO_2 nanoparticles showed ingestion linked to adverse outcome pathways such as inflammation, genotoxicity, and gastrointestinal impacts.	[6] Rolo D, et al. (2022). *Nanomaterials*, 12(19):3275.
2023	Madhyastha H.	Provided insights into genotoxic and carcinogenic potential of nanoparticles, emphasizing DNA	[7] Madhyastha H. (2023). *Materials Research Foundations*, 171.

		damage and long-term risks.	
2024	Strekalovskaya et al.	ZnO nanoparticles disrupted soil–bacterial–plant interactions, leading to reduced ecosystem stability and altered soil microbial communities.	[8] Strekalovskaya EI, et al. (2024). *Agronomy*, 14(7):1588.
2024	Ahmad & Ahmad	Reviewed nanoparticle–soil microorganism interactions in crop management, highlighting both beneficial and harmful outcomes.	[9] Ahmad F, Ahmad S. (2024). *Industrial Applications of Soil Microbes: Vol 4*.
2022	Ouyang et al.	Examined ecotoxicity of natural nanocolloids in aquatic environments, showing risks to plankton, algae, and overall aquatic health.	[10] Ouyang S, et al. (2022). *Water*, 14(19):2971.
2024	Motta G.	Proposed safety-by-design nanomaterials using in vitro toxicological testing and new approach methodologies for safer innovation.	[11] Motta G. (2024).
2024	Rattner et al.	Presented emerging technologies for ecological risk assessment of toxicants, emphasizing wildlife health and ecosystem sustainability.	[12] Rattner BA, et al. (2024). *IEAM*, 20(3):725–748.

3. Toxicological and Ecological Visions

Nanotechnology has great potential in the field of medicine, consumer products and environmental solutions, but with these potentials come great concerns about the possible negative effects of nanomaterials. The ecological and the toxicological approaches offer complementary but different perspectives on the interactions between nanomaterials and biological systems and the environment. Toxicology is more biased towards direct health effects on cells, organs and organisms, whilst ecology looks at larger scale processes in the ecosystem and biodiversity. Combined, these views emphasize the multi-scale dangers of nanomaterials, including cellular DNA harm to the breakdown of worldwide ecosystem services.

This section discusses the toxicological view in depth, including the cellular and molecular damage, respiratory effects, GI and systemic distribution, and long-term carcinogenicity before expanding the conversation to ecological implications, which impact environmental safety, sustainability and ecosystem health.

The result of such imbalance is damage to the proteins, lipids, and nucleic acids with impaired cellular signaling and energy metabolism [13].

3.1.1. Cellular and Molecular Damage

One of the most reliable of the toxicological analyses has been the capability of nanomaterials to induce cellular and molecular injury. The small particles (nanoparticles) can penetrate the cell through the biological barriers of the organism since they are very small with a high surface to volume ratio. Once internalized, they have the ability to localize in organelles such as mitochondria, lysosomes and nuclei. Such localization disrupts the activity of the organelles and causes cell stress.

Oxidative stress is one of the toxicological pathways that have been discovered. The surface properties of the majority of nanoparticles generate reactive oxygen species (ROS), overloading the antioxidant defense systems of the cell. Their cumulative nature in these organs implies the possibility of cumulative long-term and chronic toxicity. Especially important is the dysfunction of mitochondria (apoptosis (programmed cell death) and energy provision are two crucial factors that mitochondria can regulate). Damage of the mitochondrial membrane can trigger both apoptotic and necrotic cascades, and lead to dysfunction of the tissues.

Moreover, nanoparticles can also interfere with the DNA repair mechanisms. It has been shown that in the case of long-term exposure to ROS, DNA strand breaking occurs, chromosomal defects and repair enzyme activity are inhibited. Along with being linked to immediate cell death, this genomic instability is also related to long-term mutagenesis and carcinogenesis. By doing so we can provide mechanistic explanations of how nanomaterials can induce chronic disease at the cellular level [14].

3.1.2 Respiratory Effects

The respiratory tract is one of the most significant occupational exposure pathways at work, especially in the industries that produce, handle, or store nanomaterials. Nanoparticles that enter the body through the air can skip the upper respiratory system and accumulate in the bottom of the alveoli in the lungs.

In this case they stimulate fibrosis, inflammation and tissue damage. The alien substances eliminated by the alveolar macrophages can overpower the macrophages causing chronic inflammatory signals. Chronic exposure has been associated with scarring of the lung tissue, loss of elasticity and loss of gas exchange. The symptoms could be relayed to chronic coughs, dyspnea or lung deficiency similar to occupational lung diseases previously caused by asbestos and silica.

Besides local pulmonary effects, nanoparticles could also enter the bloodstream via alveolar-capillary barrier without the worry of non-respiratory systemic effects. This evidence proves the importance of occupational protection and control because among the most proximate and detrimental routes of exposure are inhalation [15].

3.1.3 D. G. I., Systemic

The other significant route of elimination is ingestion but not inhalation. The ingested nanomaterials may contain contaminated food or food wrappings, or may be ingested accidentally through the inhalation of occupational dust. Once it enters gastrointestinal (GI) tract, nanoparticles interact with epithelial cells and gut microbiota.

According to the research results, nanomaterials can cause an inflammatory condition, impaired absorption of nutrients, and microbial imbalance (dysbiosis). These changes in the gut microbiota are of particular concern due to the immunologic, digestive, and metabolic regulatory functions of the microbiome. There are numerous chronic illnesses that dysbiosis has been associated with, including inflammatory bowel disease and obesity, as well as neurological conditions.

The systemic distribution evidence is probably even more concerning. According to available literature, nanoparticles are not accumulated in the GI tract but can be transported to other secondary organs like liver, spleen, kidneys and even to the brain. The importance of this chronic spread lies in the fact that ingestion is not just a local exposure issue, but a general body exposure issue, as well. Within the liver, nanoparticles may, e.g., disrupt the detoxification processes, but once the substance is deposited in the brain, it also tends to promote neurotoxicity and therefore form connections with degenerative pathology.

Such endemic spread is important because ingestion is not only a place-based risk factor, but there is also an exposure pathway to the entire body [16].

3.1.4 Long-Term Carcinogenicity

Possible carcinogenicity is one of the most serious toxicology issues. It has been long linked with DNA fragmentation, mutation and genomic instability as a long-term outcome of nanomaterial exposures. Those are the typical processes of cancer formation and evolution.

The risk seems to be especially great in tissues that are regularly exposed or are the primary locations of deposition, like the lungs (trough inhalation), liver (via systemic circulation) and gastrointestinal tract (via ingestion). Another common outcome of nanoparticle exposure is chronic inflammation, which also exposes cells to a pro-carcinogenic environment by facilitating oxidative DNA damage and cellular signalling pathway changes.

The relative modernity of nanotechnology and the existing mechanistic data in the form of in vitro and animal experiments not only favor high precautions in humans, but there is no definite epidemiological evidence to support this claim. There is an urgent need to conduct longitudinal studies on human being to either prove or disprove these problems particularly among occupationally exposed population [17].

3.2 Ecological Perspectives

Ecology is a broader view as toxicological studies involve people and processes at the cell level, since it focuses on nanomaterials and the ecosystem. In this case one is not speaking of organ-specific effects but of disruption of the ecological processes and services.

3.2.1 Agriculture and Soil Systems

The nanoparticles that enter the environment have a higher chance of accumulation in soil systems where they encounter microorganisms, earthworms, and plant roots. The recycling of nutrients and the decomposition of organic materials as well as soil fertility depend on the soil microbial community. There is however some evidence that nanoparticles reduce the microbial richness, enzyme activity and change the fixation of nitrogen.

This is quite catastrophic given the case of agriculture. With bad soils, there is low productivity of crops and it poses a risk to food security. Additionally, nanoparticles, which are being absorbed by plants, may be stored in the edible tissues and constitute a route of human ingestion via the food chain.

3.2.2 Aquatic Ecosystems

Another area of concern is the aquatic ecosystems. Nanoparticles are introduced into water through industrial effluent, run-offs and deposition. In the vast majority of cases, they mix with planktons, algae, fish, and other processes within a water system in an interruptive way.

Nanoparticles as an indicator can inhibit photosynthesis in algae and slow down the creation of oxygen and destabilize the foundation of the water food chain. Besides threatening the health of fish, bioaccumulation in fish tissues poses a threat to the health of humans who consume contaminated seafood. Moreover, the ecology of the sediments may also be disturbed by the aggregation of nanoparticles in the water.

3.2.3 Biodiversity and Ecosystem Services

The capability of nanomaterials to produce cellular and molecular damage has been among the most reliable of the toxicological studies. The nanoparticles bypass the biological barriers and metastasize into the cell due to the ultra-small size and high ratio of surface-to-volume. Once internalized, however, they can localize in organelles such as mitochondria, lysosomes, and nuclei. Such localization disrupts the work of the organelles and causes cell stress.

Oxidative stress is one of the toxicology pathways that have been discovered. Most nanoparticles have surface properties that generate reactive oxygen species (ROS), which overwhelms the antioxidant defense of the cell. The accumulation in these organs is an indicator that there may be long-term and chronic accumulated toxicity. Of special interest is the mitochondrial dysfunction (apoptosis (programmed cell death) and energy supply are significant factors that mitochondria regulate). Damage of the mitochondrial membrane can trigger pro-apoptotic or necrotic cascades and lead to dysfunction in the tissues.

Also, nanoparticles can interfere with the repairing process of DNA. It has been shown that chronic exposure to ROS causes strand breakages of DNA, aberrations of chromosomes and reduces repair enzyme efficiency. Not just is this genomic instability linked to immediate cell death, but it is also a cause of long-term mutagenesis and carcinogenesis. By so doing, the cellular-level data may provide concrete mechanistic explanations of how nanomaterials may lead to chronic disease [14].

3.1.2 Respiratory Effects

One of the largest occupational exposure routes is the respiratory system, particularly in those industries that produce, work with, or use nanomaterials. The inhaled nanoparticles may bypass the upper respiratory defenses and be deposited deep in alveolar regions of the lungs.

In that instance, they provoke fibrosis, inflammation and structural damage. The foreign particles clearing the alveolar macrophages may overwhelm the alveolar macrophages and lead to chronic inflammatory signaling. Scarring of the lung tissue, loss of its elasticity, and loss of gas exchange have all been linked to chronic exposure. The symptoms may be interpreted as chronic coughing, dyspnea or loss of lung volume as was already experienced in occupational pulmonological illnesses previously caused by asbestos and silica.

In addition to local lung effects, nanoparticles may also cross the alveolar-capillary barrier into the bloodstream with concerns over systemic effects outside the lung. Such evidence underscores the importance of workplace protection and regulation since inhalation is one of the most direct and hazardous exposures [15].

Gastrointestinal and Systemic Distribution This section examines the gastrointestinal and systemic distribution in relation to the pathogenesis of the early disease.

Other significant routes of elimination other than inhalation are ingestion. Ingested nanomaterials can be present in contaminated food or food wrapping, or can be accidentally ingested by occupational dust. Once in the gastrointestinal (GI) tract, nanoparticles are going to react with epithelial cells and gut microbiota.

A study demonstrates that nanomaterials may lead to inflammation, disturbance of nutrient absorption, and disturbance of microbial balance (dysbiosis). The alteration of gut microbiota is especially disturbing given the immunological, digestive, and metabolic regulation roles of the microbiome. Dysbiosis has been linked to many chronic diseases such as inflammatory bowel disease and obesity and neurological disorders.

Evidence of systemic distribution may be even more concerning. The literature shows that nanoparticles are not concentrated in the GI, but could translocate in other secondary tissues such as liver, spleen, kidneys and even in the brain. This endemic is important because ingestion is not just a local risk, but a pathway to a general body exposure. In the liver, nanoparticles have the potential to interfere, e.g., with detoxification processes, and their presence in the brain poses neurotoxicity risks as well as forming links with degenerative pathology.

This endemic dissemination is significant since ingestion is not just a topographical threat, but a pathway to overall body exposure [16].

3.1.4 Long-Term Carcinogenicity

One of the gravest toxicological concerns is possible carcinogenicity. Long-term exposure to nanomaterials has been associated with DNA fragmentation, mutation and genomic instability. All these happenings are typical of cancer development and progression.

Its threat appears to be particularly acute in those tissues which are either actively exposed to it or serve as the major deposition sites such as the lungs (through inhalation), liver (through the systemic circulation) and the gastrointestinal tract (through ingestion). Chronic inflammation is another typical consequence of nanoparticle exposures, and can predispose cells to a pro-carcinogenic environment by promoting oxidative damage of DNA and alterations in cellular signalling pathways.

In humans, there is still a lack of definite epidemiological evidence despite the fact that, due to the relatively new introduction of nanotechnology, the mechanistic information that can be retrieved through in vitro and animal experimentation does provide a high state of precaution. Longitudinal studies of human beings are urgently required to either confirm or refute these issues in occupationally exposed populations [17].

3.2 Ecological Perspectives

Since toxicological studies concern individuals and processes at the cellular-level, ecology is a broader perspective because it is concerned with the interaction between nanomaterials and the ecosystem. In this instance, it ceases to be a question of organ-specific effects but an issue of ecological process and service disruptions.

3.2.1. Agriculture and Soil Systems

Nanoparticles released into the environment are likely to become concentrated in the soil systems where they are exposed to microorganisms, earthworms, and plant roots. Soil microbial communities are essential to recycle nutrients, decompose organic matter, and make soils fertile. However, they are showing signs of nanoparticles decreasing the microbial diversity, the enzyme activity and altering the nitrogen fixation.

This is particularly disastrous given the situation in agriculture. Less fertile soil reduces crop production, and it is a threat to food security. Further, nanoparticles absorbed by plants may enter the edible tissues, offering human a path of ingestion through food chain.

3.2.2 Aquatic Ecosystems

The other significant area of interest is aquatic ecosystems. One of the ways in which nanoparticles end up in water bodies is through industrial effluents, runoffs and deposition. In most cases, they interact with planktons, algae, fish and other aquatic processes in disruptive ways.

3.2.5 Table 4.1: Summary of Toxicological Findings

Theme	Key Findings
Cellular damage	Oxidative stress, mitochondrial dysfunction, apoptosis
Respiratory effects	Pulmonary inflammation, fibrosis, reduced lung capacity

Gastrointestinal effects	Inflammation, microbiota imbalance, nutrient absorption issues
Systemic distribution	Nanoparticle migration to liver, spleen, brain, kidneys
Long-term carcinogenicity	DNA fragmentation, mutations, increased cancer risk

3.2 Ecological Perspectives

Pollution of Soil and Microorganisms

The result indicated that the nanomaterials are likely to be deposited in the soils due to industrial emission, sewage sludge and solid waste. As they establish themselves, they disrupt the microbial communities by interfering with the fixation of nitrogen, interrupting the functioning of enzymes and reducing soil fertility. This improves the nutrient cycle and hence plant growth and stability of the ecosystem.

3.3.2 Growth of plants and photosynthesis

It was discovered that introduction of nanomaterials into soil or water systems influenced the growth of plants. The other nanoparticles inhibited seed germination, slowed root growth, and chlorophyll. The impact to photosynthesis led to the poor crop production to create fear to the people about food safety and food sustainability [28].

3.3.3 Aquatic Toxicity

This resulted in aquatic environments being highly polluted with direct dumping of nanomaterials to wastewater streams. It was also found that fish had developmental defects, reproduction was lowered in aquatic invertebrates as well as the feeding habits of other animals like daphnia. Bioaccumulation in water food webs also occurred, nanoparticles were transmitted to fish through algae- small crustacean pathways and it is expected that trophic transfer of nanoparticles to humans will occur through fish [27].

3.3.4 Ecosystem and biodiversity stability

The ecological evidence of decreasing biodiversity in the ecosystems remaining on nanomaterials was more. A combination of interference with microorganisms, plants and aquatic organisms led to destabilised ecosystems. Among the risks identified in the evidence are a reduction in ecosystem services such as soil fertility, clean water, and food chain integrity, which are all mandated by human health.

3.3.5 Table 4.2: Summary of Ecological Findings

Theme	**Key Findings**
Soil contamination	Reduced microbial diversity, impaired nitrogen fixation
Plant effects	Reduced germination, stunted root growth, lower chlorophyll levels

Aquatic toxicity	Developmental deformities, reproductive decline, altered behaviours
Biodiversity impacts	Loss of ecological balance, reduced ecosystem services
Bioaccumulation	Trophic transfer of nanoparticles across aquatic food chains

3.3 Comparative Insights

The convergence of toxicological and ecological perspectives is made under the 4.4.1 heading. One of the key intersections is that of oxidative stress. This was found in human cells as well as in environmental organisms and indicated a common pathway of nanomaterial toxicity. Likewise, bioaccumulation was observed both in the domains of nanoparticles accumulating in human organs and in aquatic organisms, and was persistent across biological systems.

3.4.2.D.D. Dissimilarity of the Perspectives

The fundamental differences were due to the extent and breadth of analysis. Toxicological analyses of cellular and organ-level effects and ecological analyses of population and ecosystem effects were done. A second discontinuity was that even those nanomaterials that were deemed to have a relatively low risk to human health would present a major ecological disturbance, especially in plants and aquatic organisms.

3.4.3 Overlapping Concerns

Risks of chronic exposure, cumulative effects, and absence of long-term data were also identified in both perspectives. Overlapping regulatory issues were also present, with current systems tending to view nanomaterials as traditional chemicals, and missing nanospecific characteristics.

Comparative Analysis of Toxicological and Ecological Findings of Nanomaterials

Aspect	**Toxicological Findings**	**Ecological Findings**
Mechanisms	Oxidative stress, DNA damage	Oxidative stress, disruption of metabolic processes
Bioaccumulation	Liver, spleen, brain, kidneys	Algae → invertebrates → fish → higher trophic levels
Exposure duration	Chronic exposure linked to cancer, organ failure	Chronic exposure linked to biodiversity loss
Scale of impact	Cellular, organ-specific	Population, ecosystem-level
Regulatory challenges	Limited toxicological safety standards	Limited ecological risk frameworks

4.0 Comparative Discussion Toxicological vs Ecological Themes

One of the most radical fields of modern science and technology is nanotechnology, and nanotechnology is used in medicine, consumer goods, agriculture and environmental remediation. However, it is also urgently needed to re-evaluate the adverse effects of nanomaterials in human systems (toxicological) and in environmental systems (ecological). This comparative discussion identifies the similarities and differences between the toxicological and ecological findings and makes conclusions on the practical implications to the population, environmental sustainability and industrial development and theoretical contribution, practical implication, gaps in knowledge and future research.

4.1 Toxicological vs. Ecological Effects

The most fascinating implications of the results are that, nanomaterials toxicology and ecology seem to follow the same mechanistic pathways-mainly, oxidative stress, inflammation, DNA damage and bioaccumulation. These cross streets despite these, the fields separate in the scope and direction of investigation.

Research in toxicology tends to focus on the effects on the health of cells and individuals. On the indicative side, inhaled nanoparticles may penetrate deep into the lungs to a point of fibrosis, chronic inflammation or even carcinogenesis. Reactive oxygen species (ROS), mitochondrial dysfunction, and DNA strand breaks are biomarkers of interest to toxicologists as early indicators of disease progression.

The other ecotoxicology is about the larger processes within the ecosystem. Oxidative stress can induce similar cellular-scale damage to aquatic organisms or plants, but the impact becomes greater, to the point that an entire population and food chains may be at risk. Significantly, the nanoparticles imported into the water systems could have an impact on the microbial communities, which are part of the vital nutrient cycling functions. This disruption of microbial functions extends to higher trophic levels, which ultimately poses a threat to biodiversity, agricultural productivity and ecosystem services.

The other difference branch is exposure pathways. The exposure in humans is usually occupational in nature, either by medical equipment or consumer products or infected food. Exposure pathways are no longer as localized in the ecosystem and can be via atmospheric deposition, run-off into rivers, plant uptake or bioaccumulation in aquatic organisms. Such a systemic distribution complicates ecological fate in that the fate and delivery of nanomaterials is influenced by ecological differences by pH, salinity and organic materials content.

It is thus very obvious that, though toxicology gives us everything that we must know about the molecular background of damage, ecotoxicology give the harms in the systemic processes. This feature of bringing these views to the ground is quite crucial since one simply cannot talk about human health without the aspect of ecosystem stability. Indicatively, nanoparticles that interfere with the normal operation of microorganisms in soil lower crop yield that directly influences the food security and nutrition of humankind. This reliance underscores the importance of the One Health research paradigm based on synthesis of molecular toxicology and ecological products to create a cumulative view on the risks of nanomaterials [19].

Conclusion about what the Research says on Public health, environmental safety and Industry.

4.2.1 Public Health

The toxicological evidence has a direct health impact on the population. The nanotechnology industries have a high-risk population due to the chronic occupational exposures the workers are exposed to. These workers may also be put at risk of increased respiratory disease, systemic poisoning or cancer due to failure to observe the precautionary measures. Nanoparticles can also be exposed to consumers not at the workplace via food wrappings, cosmetics or drugs. Small size and the high surface reactivity of nanomaterials create specific physicochemical characteristics that allow nanomaterials to cross biological barriers and travel throughout the body, raising the question of accumulation with time in body organs.

Furthermore, long term, low dosing is of particular interest. Acute toxicity is not necessarily evident, but a small subclinical effect can accrue through years to produce cardiovascular, neurological, or metabolic disorders. The public health surveillance systems would then have to be re-tuned to identify exposures to nanoparticles in addition to the known chemical hazards.

4.2.2 Environmental Safety

Nanomaterials are highly ecologically toxic. Their homogeneity in soil can alter the functionality of microbial communities, therefore, reducing the fertility and agricultural productivity of the soil. Wet ecosystems are specifically at risk: nanoparticles may affect the biomass of plankton, can affect the photosynthesis of algae and accumulate in fish tissues, thus, entering the human food chain.

Human health outputs cannot be disaggregated of the ecological consequences. Clean water, fertile soil, and biodiversity are the basic services present in the ecosystems and on which the well-being of man lies. Nanoparticles that pollute these services endanger the living environment and the sustainability of human life. Thus, the issues of ecological safety include not only loss of biodiversity, but also social and economic stability, particularly in those areas where individuals rely on the nature resources as a livelihood.

4.2.3 Industry and Innovation

Commercialising the findings is twice as difficult. On the one hand, nanomaterials have no analogs with regard to its technological worth - the performance of the product, medical innovation and cost-competitive advantage. On the contrary, the toxicological and ecological hazards require a timely commitment in sustainable design.

Today there is an increasing pressure on industries to at least consider life-cycling analysis when identifying the environmental impact not just in the creation of nanoparticles, but also in the disposal of nanoparticles. Biodegradable or less persistent nanomaterials is the way to go. Besides, the industries can expect that the regulatory action will be more stringent and that their production process will be changed so that it not only complies with the standards, but also ensures the consumers.

4.3 Theoretical Contribution

The review will help in advancing the theoretical knowledge of nanotoxicology/ecotoxicology by bringing together two historically independent research domains. Unlike the propensity of toxicology to isolate cellular or organ end points, ecotoxicology affirms harm in context, as being a component of an ecosystem. The data in the review cross the border of any discipline as it found the common way, including oxidative stress, inflammation, DNA damage and bioaccumulation.

The most significant theoretical advancement is the argument in favour of a One Health approach. One Health is an interdisciplinary approach recognizing the interdependence of animal, environmental and human health. In the context of nanomaterials, this model links molecular toxicology to ecological systems, and encourages the kind of research that regards worker exposure, consumer safety, and ecosystem stability as co-existing factors. Such a holistic perspective also urges researchers and policymakers to transcend singular approaches in favor of integrative approaches [20].

Comparative Exposure Pathways of Nanomaterials

Pathway	**Human Exposure (Toxicological)**	**Environmental Exposure (Ecological)**	**Key Risk**
Inhalation	Occupational workers inhale nanoparticles in industries	Airborne deposition of nanoparticles affecting plants & animals	Respiratory illness, reduced air quality
Ingestion	Contaminated food packaging, additives, water	Soil → plants → food chain transfer	Gastrointestinal issues, food insecurity
Dermal Absorption	Cosmetics, lotions, medical patches	Surface water contact, soil exposure for terrestrial organisms	Skin irritation, ecological imbalance
Medical Applications	Intravenous drug delivery, diagnostics	Disposal of nanomedical waste into landfills/water	Systemic toxicity, leaching into ecosystems
Bioaccumulation/Biomagnification	Accumulation in liver, kidneys, brain	Aquatic organisms → fish → humans	Chronic disease, ecosystem disruption

Comparative Regulatory & Research Gaps

Aspect	**Human Toxicology**	**Ecotoxicology**	**Overlap / Gaps**
Research Focus	Cellular, organ-specific (short-term, high dose)	Population, ecosystem-level (lab-based, simplified)	Lack of long-term, low-dose studies
Standards & Regulations	Occupational exposure limits, consumer safety	Environmental quality standards (limited)	No nanospecific unified framework
Data Availability	Some mechanistic & medical models	Fragmented ecological data, fewer longitudinal studies	Few integrated datasets

Risk Assessment Approaches	Based on chemical analogies	Based on species/ecosystem responses	Not harmonized across domains
Future Needs	Long-term epidemiology, realistic exposure models	Field-based ecological studies, biodiversity monitoring	One Health & cross-disciplinary integration

4.4 Practical Consequences

4.4.1 Regulation and Risk Assessment

The results underscore the weakness of the current regulatory criteria that will subject nanomaterials to the same regulations as conventional chemicals. But since the peculiarities of nanomaterials, i.e. high reactivity, small sizes and possible bioaccumulation, the nanospecific requirements are required. The toxicological and ecological data must be incorporated in risk assessment and must also be premised on actual exposures and life-cycle effects. Standards across national borders are also significant, as nanomaterials are transported at national borders not only through trade but also through the environment.

4.4.2 Green Nanomaterial Design

The second implication in practice is that green nanomaterial must be designed. Researchers and industries require the production of less persistent, less bioaccumulative and more degradable nanoparticles in the natural environment. The innovation of nanomaterials should also incorporate the concept of green chemistry since long-term safety is not undermined by technological advancement. A case in point is that the toxicity of nanoparticles may be minimized by using surface modification methods or by the biodegradable carriers breaking down in the environment after deposition.

4.4.3 Social and professional responsibility and safety at work

Lastly, the study also establishes the social awareness significance concerning the hazards of nanomaterials. Safety awareness regarding the handling and disposal of products containing nanomaterials can be developed. As a precaution, the workplace needs tighter occupational safety requirements (ventilation, protection equipment and exposure monitoring). The employees and the customers will be educated and trained to do a better job and to win the trust of the people on nanotechnology.

4.5 Limitations of Knowledge

In spite of these advances, there are several limitations in the present body of research.
The literature is filled with short term laboratory studies. In such experiments, high amounts of nanoparticles are typically employed and may not be the actual exposures in the real world. This leaves it unclear how much of the risks in chronic, low-dose conditions are real.
Particularly in human beings, the long-term effects are ill-established. Nanoparticles might be bioaccumulative in organs with latent effects, which are yet to be realized in the short-term experiments.

The studies which have investigated ecology are still disjointed and the majority of them do not project future projections. Most of the research is devoted to the short-term responses of ecosystems to stressors when, in reality, it takes years to see the impact of stressors.
There is also no comparative studies, which would bridge the knowledge gap existing between the ecological and the toxicological outcome. The disjunction which needs to be conquered is to form a total perception.

The shortcomings reflect the methodological cleverness and interdisciplinary synergies to focus on the vast pool of risks posed by nanomaterials.

4.6 Future Research Directions

The following research priorities of the future are established in the review:
Long-term, low-dose: To detect minor but significant effects of a long exposure, long-term studies are needed in humans and ecosystems.

It must be realistic experimental models: The conditions under which experimental is fulfilled in the laboratory should be closer to the natural conditions, and the conditions under which the experiment is performed are variable such as pH, salinity, and interactions between microbes.
Combination of ecological and toxicological instruments: There is a need to conduct studies within the framework of the One Health system, which means that the health of both the environment and people must be considered simultaneously.
Relate ecology and epidemiology: Research should fill the gap: Research should link epidemiological measures of human health with ecological field data, which will give cross-scale data.

Green design innovation: Biodegradable, less bio-accumulative, and environmentally friendly nanomaterials, invention of such nanomaterials should be given priority in order to make the technological invention safe.

5.0 Conclusion/Recommendation

5.1 Conclusion

It was the purpose of the writing of this Review Paper, to read into the toxicological and ecological approaches to nanomaterials, so as to get some comparative data, and to get a better idea of the risks, and, in general, of the reality of using nanomaterials. This qualifies as a thematic contribution to the topic because it is a synthesis on the available evidence on the topic by conducting a secondary qualitative research in order to produce a contribution to the theme of the effect of nanomaterials on human health and environment.

Those were indicative of the toxicological risks being mostly cellular and organic in nature and may be associated with oxidative stress, DNA damages, systemic distribution with consequent long term health effects, including respiratory disease and carcinogenicity. In the ecological dimension we learnt that nanomaterials have been found in soil, have disrupted microbial and plant systems, aquatic systems and biodiversity. Similar mechanisms such as oxidative stress and bioaccumulation can be compared in these two fields except that in toxicology, the focus is on the impact on the health of an individual; in ecology, the focus is on the impact on a population and ecology.

As a result of comparative analysis, all these effects were interrelated and human health or environmental well-being could not be addressed as two independent variables. Nanomaterials that are disrupted may threaten food security and clean water, and that lead to human toxicity can also disrupt ecological stability through waste and emissions. Such interventions are justified by the following factors: these observations, the necessity to implement the risks in a multifaceted way, within the One Health approach, and others.

It was also found that there were some significant gaps in the knowledge being researched. Long term/low dose effects remain unknown and most of the studies carried out have been done on short term/high dose exposures. Similarly, intricacies of reality world are indescribable because no coordinated studies of human and environment have been undertaken. Regulatory schemes remain pre-modern and tend not to take adequate notice of the nanospecific nature of nanomaterials but instead cluster them together in ordinary chemicals.

In short, nanomaterials have opportunities and threats. They need to be discussed within the context of their ecological and toxicological effect as they offer stimulus to creativity across numerous unrelated industries and their outcomes can prove catastrophic to sustainability of human living and the natural environment.

5.2 Recommendations

As a result of the findings it is suggested that the following should be recommended:

Adopt Regulatory Approaches

Regulatory bodies must develop nanospecific regulations which deal with both toxicological and ecological risks. This is combined with mandatory occupational and consumer exposure risk assessment, enhanced occupational and consumer exposure investigation [22].

Advance Nanomaterial Sustainability

Development of biodegradable and less persistent nanomaterials should begin to attract the attention of scientists and manufacturers. Production processes must undergo life-cycle analysis when there is the reduction of long term risks of ecological and health problems [23].
Improve Population and occupational Safety.

A clear policy regarding the management, storage and disposal of nanomaterials in workplaces should be in place. Education of consumers about safe use of products and higher risk that nanotechnology products pose on human being can also be carried out through public awareness.

Spur Multidisciplinary Research

The cross-disciplinary approach should in the future incorporate toxicology research into the ecological approach. A combination of epidemiology, ecotoxicology and materials science would be a better way to evaluate the risks.

Invest in long-term and realistic Research

This would channel the funds into longitudinal research studies concerning low-dose exposures of chronic duration in human beings and ecosystems. Without natural settings and field experiments, there are no possible laboratory experiments.

Become One

One Health is the practice where policymakers, researchers, and industries can consider risks of nanomaterials as interdependent given that human health and the environment depend on the sustainability and resilience of the ecosystem [24].

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