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A Diagrammatic Mini-Review on the Soil-Human Health-Nexus: with a Focus on Soil Nano-Pollution

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ENVIRONMENTAL pollution is a great modern challenge. This pollution is generated from different sources and reaches a variety of environmental compartments including soil, water, plants, air, animals, and humans. Among sources of pollution, nanopollution has become an emerging global issue. Nanopollution is a result of the intensive processing and use of nanomaterials and/or nanoparticles in the soil, water, plant, air, and food chain systems. Ultimately, nanopollutants may reach humans and influence their health. Health problems reported after human exposure to nanopollutants include toxicity to the kidney, brain, spleen, and heart. Approaches to remediate soil nanopollution will be discussed in this review, which focuses on soil nanopollution in the frame of soil-human health nexus (SHHN). A close relationship between soil nanopollution and the SHHN has been confirmed by several studies. This interaction depends on several factors related to the pollutants, their concertation, and agro-environmental conditions. The interaction between soil nanopollutants and human health is of great concern and needs more study.

Keywords: Nano-pollutants; Nano-remediation; Nano-medicine; Nanotoxicology.

1. Introduction

Pollution is a great challenge facing countries all over the world. This pollution represents a great threat to human health, and new sources of pollutants, such as nanopollutants, are frequently documented. Nanopollutants have emerged as a concern because of the intensive application of nanoparticles and/or nanomaterials in nearly all sectors of modern life. Nanomaterials or nanoparticles may have either natural or artificial origins. The main natural sources of nanoparticles (NPs) include NPs (1) expelled by volcanoes, (2) from ocean spray, (3) in mineral composites, and (4) in natural polymers/nanocomposites (Adhikari and Dharmarajan 2021; Matei et al. 2022). Artificial sources of nanoparticles that are likely to cause environmental pollution include (1) industrial effluents (e.g., sewage sludge, energy generation, mining, vehicle wastes, textile wastes, industrial medicine, etc.), (2) agro-activities such as NPs in agro-chemicals (nanofertilizers, nano-pesticides, nano-amendments, etc.), (3) NPs generated from agro-machinery during cultivation and harvesting, and (4) NPs resulting from post-harvesting processes (Bouyahya et al. 2022; Jan et al. 2022).

Nanopollution can be defined as the generic name for all waste generated in the environment by nano-devices or during manufacturing processes of

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nanomaterials, where these nano-wastes are released into the environment and reach humans (Biswas and Sarkar 2019). Nanopollution can be found in the soil (Adhikari and Dharmarajan 2021), aquatic environments (Biswas and Sarkar 2019; Lehutso and Thwala 2021), food (Karimi et al. 2018), and plant systems (Rizwan et al. 2021; Bouyahya et al. 2022; Murali et al. 2022). The increasing use of NPs in different sectors and for commercial purposes has increased their risks to the environment and to human health (Jan et al. 2022). These risks may result from the direct and/or indirect exposure to NPs. Therefore, urgent research is needed to determine the expected toxic effects of a variety of NPs on the entire environment and human health (Jan et al. 2022). On the other hand, many studies have discussed the potential of nanoparticles or nanomaterials to remediate polluted soils (e.g., Boregowda et al. 2022; Rajput et al. 2022).

This mini-review focuses on soil nanopollution from perspective of human health. It will address sources of NPs, their fate and expected behavior, in soil, and routes of exposure for humans. Expected direct and indirect links between soil and human health in frame of soil nanopollution will be discussed. The possible remediation of nano-pollutants in soils also will be investigated.

2. Nanopollution: An Overview

Due to the intensive application of nanoparticles in almost all sectors in our life, several nanopollutants are found in different environmental compartments (e.g., soil, water, air, plants, and humans), as presented in **Table 1**. Nanopollution in soil is of great concern (Adhikari and Dharmarajan 2021). These pollutants may negatively impact soil ecology, crop production and/or quality, ground water purity, and human health. Therefore, there is an urgent need to develop a safety protocol for different nanopollutants to protect our environment and ecology.

Nanopollutants may be either natural or artificial. Natural sources of NPs include (1) volcanic ejecta, (2) ocean spray, (3) mineral composites, and (4) natural polymers/nanocomposites (**Figs. 1 and 2**). Artificial sources include (1) industrial effluents (e.g., sewage sludge, energy generation, mining, vehicle wastes, textile production, industrial medicine, etc.), (2) agro-chemicals such as nanofertilizers, nano-pesticides, and nano-amendments, (3) NPs generated by agro-machinery during cultivation and harvest, and (4) those that result from post-harvesting processes. A classification of nanopollutants based on their source is shown in **Fig. (3)**.

3. Soil nanopollution as a threat for human health

Soil has a very close association with different compartments of the ecosystem (hydrosphere, atmosphere, biosphere, and anthrosphere). Several nexuses linking soil to these systems have been investigated, such as soil–water–climate change (Koriem et al .2022), soil–food–environment–health (Gu et al. 2021), soil health–human health (Rekik and van Es 2021), soil–water–plant–human (Brevik et al. 2022), and soil-human health (Omara et al. 2022) among others. Diagrammatic articles are highly effective at communicating these complex nexuses (El-Ramady et al. 2022a, b). Several recent investigations of these nexuses have used diagrams such as illustrations and/or photographs, such as soil-human relationships (El-Ramady et al. 2022c), management of salt-affected soils (El-Ramady et al. 2022d), and the soil–water–plant–human nexus (Brevik et al. 2022), along with other issues like smart agriculture (Abdalla and El-Ramady 2022), the comparison of higher plants and mushrooms (El-Ramady et al. 2022e), nano-farming (Abdalla et al. 2022), and nano-grafting (Bayoumi et al. 2022). The main difference between a typical review article and diagrammatic review is that the pictorial review heavily depends on presenting the available information using diagrams, photographs, and other image-based methods. The fundamental idea of this kind of presentation is that one photo or other image may be better than 1000 words, and therefore a well-illustrated review facilitates communicating the main ideas in the paper within the illustrations (El-Ramady et al. 2022a).

Many human health problems are a concern with nanopollution (**Fig. 2**). Although there are several kinds of pollutants, nano-plastic is considered a serious problem for human health as reported by several articles (e.g., He et al. 2021; Cárdenas-Alcaide et al. 2022; Huang et al. 2022; Lai et al. 2022; Zhou et al. 2023). Multiple risks to ecosystem and human health have been confirmed and associated with nano-plastics (Lai et al. 2022); their adverse effects on human health could occur through uptake and translocation pathways (**Fig. 4**). Nano-pollutants can enter the human body through:

1- The respiratory system: nanopollutants as aerosols directly applied in nasal or oral cavities; those that make it through air filters and breathing masks; ambient airborne.

2- Skin: through wound dressings; antibacterial textiles (e.g., sheets, towels, socks, underwear, fitness wear); antibacterial surfaces, cosmetic products (e.g., lotions, roll-on deodorants, hair products); computer hardware and mobile devices.

3- Reproductive system: through contraceptive devices; women's personal hygiene products,

4- Circulatory system: through intravenous injection of nano-enabled drugs or diagnostic system implant, medical catheters.

5- Gastrointestinal tract: through cooking utensils and coatings or food packaging, health supplements, water filters and oral hygiene products (e.g., toothpaste, toothbrushes) (Kamal et al. 2021).

Table 1. A list of some recent publication on nanopollution, their subject related to human health.

Nanopollution type	**The main findings of the study**	**Refs.**
Soil nanopollution	Nanopollution in soil and their emerging concerns and risks	Adhikari and Dharmarajan (2021)
	Possible effects of glass nanopollution on soil-plant system, on marine, terrestrial environments and affects food web	Kumari et al. (2022)
	Study the problems resulted from nano-bioremediation of pesticides from the contaminated soil	Singh and Saxena (2022)
	Remediation role of nano zero valent iron combined with earthworm in polluted soil with polychlorinated biphenyls	Zhang et al. 2023
Water nanopollution	Study and assessment of nanopollution resulted from different commercial products in water environments (sunscreens, body creams, sanitizer, and socks), which mainly contain $nTiO_2$, nAg, and nZnO	Lehutso and Thwala (2021)
	Nanopollution in the aquatic environments including phytoplankton, bacteria, zooplankton, and fish, their toxicological responses	Biswas and Sarkar (2019)
	Nanoremediation using nanomaterials including metal, carbon, polymer, and silica employed for water, soil, and air remediation	Del Prado-Audelo et al. (2021)
	Study nano-plastics in bottled drinking water, which has difficulties in their isolation and analysis. Nano-plastics may pose higher risk to human health than micro-plastics	Huang et al. (2022)
Nanopollution and plants	NPs-nanopollution in soil at the rhizosphere level, and their impacts on cultivated plants with focus on the effects of these NPs on plant producing primary and secondary metabolites	Bouyahya et al. (2022)
	Long-term uncertainty of biodegradable mulch film residues associated microplastics pollution on plant-soil health. Bioplastics are much easier to form nano-plastics and cause stronger toxic to plants	Zhou et al. (2023)
Nanopollution in soil-plant system	Soil nano-plastic pollution and its implications on soil-plant system through its impacts on nitrogen cycling and soil microbial activity	Iqbal et al. (2020)
	Nano-plastic pollution has ecological influence on soil-plant system and human health and can be transferred through the food chains	Allouzi et al. (2021)
	Nano-agrochemical ZnO toxicity reduced microbial activity, carbon, and nitrogen cycling of applied manures in the soil-plant system	Shah et al. (2022)
Nanopollution and food chain	Nanopollution of plastic can impact on metabolic disorders, neurotoxic, genotoxic, and cytotoxic are major health risks when beverages and edible foods may intake to humans	Kumar et al. (2022)
	Nano-plastic contaminations from soils to plants, which may cause human food risks through the cycle pathway of soil-plant-food	He et al. (2021)
	Pollution resulted from micro- and nano-plastics in human food chains may allow food being a threat to health safety	Al Mamun et al. (2022)
Nanopollution and microorganisms	Nano-plastics pollution and other persistent pollutant in the environment as emergence of antimicrobial resistance	Gaur et al. (2023)
	Using microorganism as and green methods in mitigating environmental impacts of nano-plastics pollution	Cárdenas-Alcaide et al. (2022)

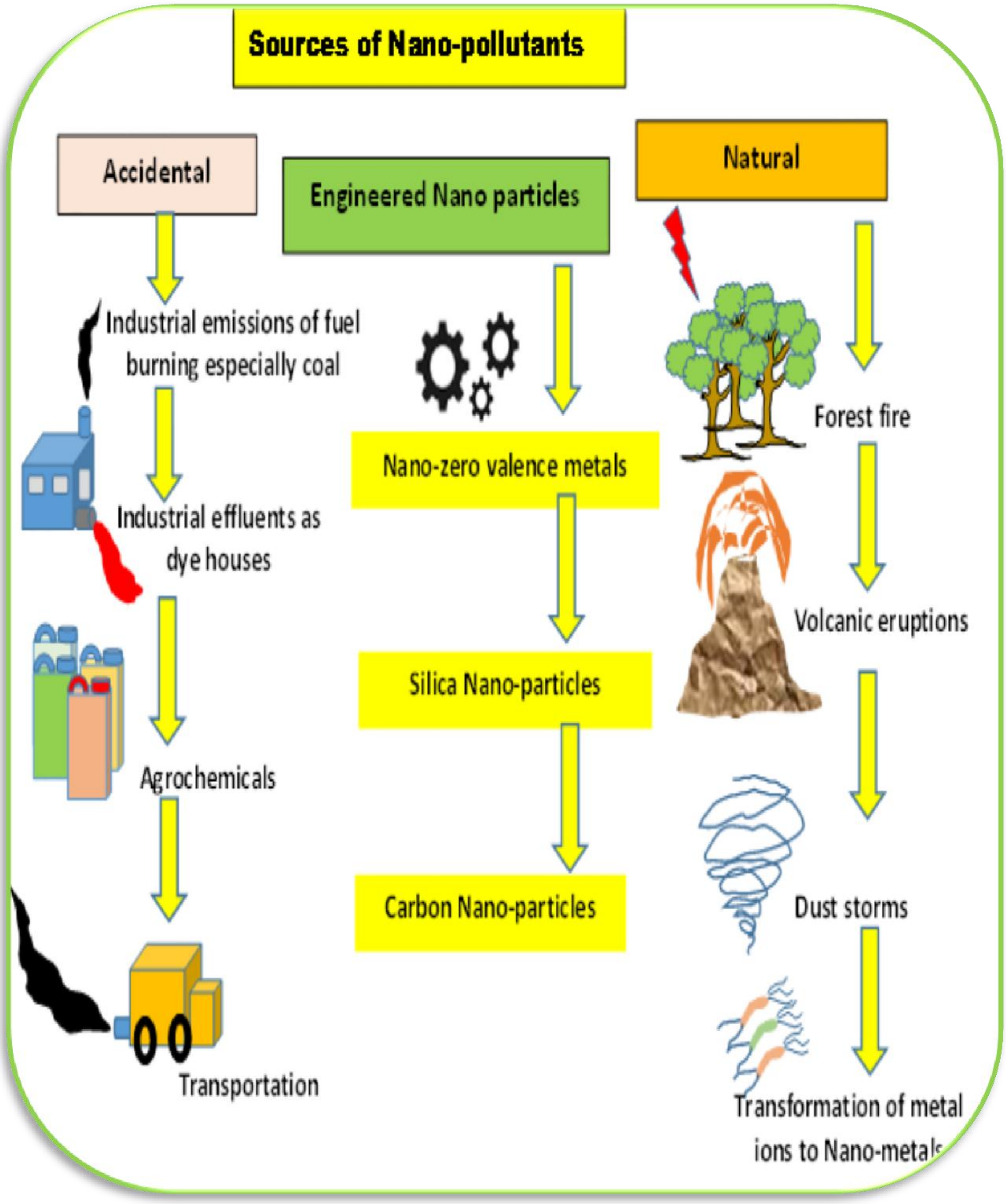

Fig. 1. Different possible sources of nanopollutants (adapted from Kamal et al. 2021).

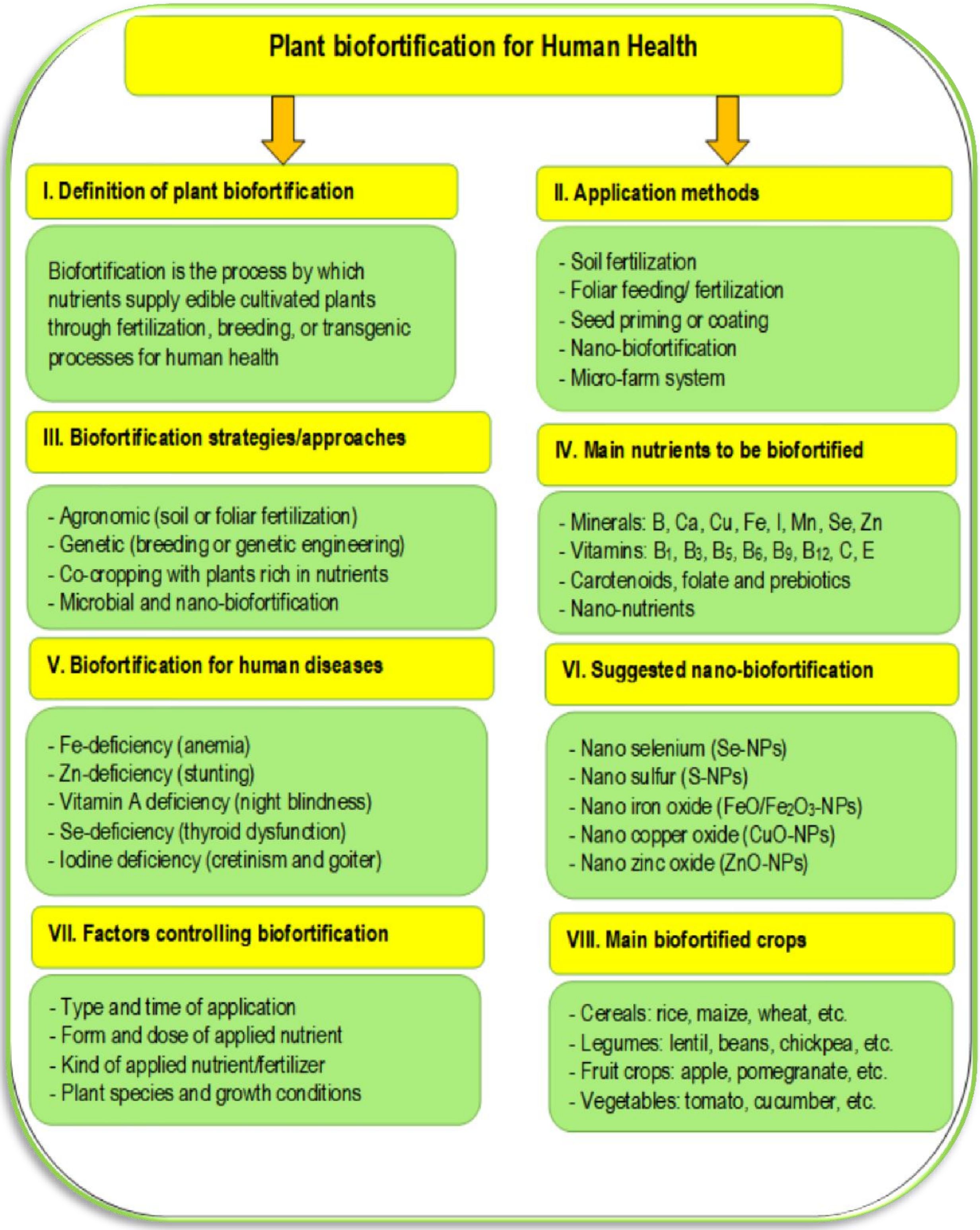

Fig. 2. General information on nanopollution, sources, forms, and their impact on human health.

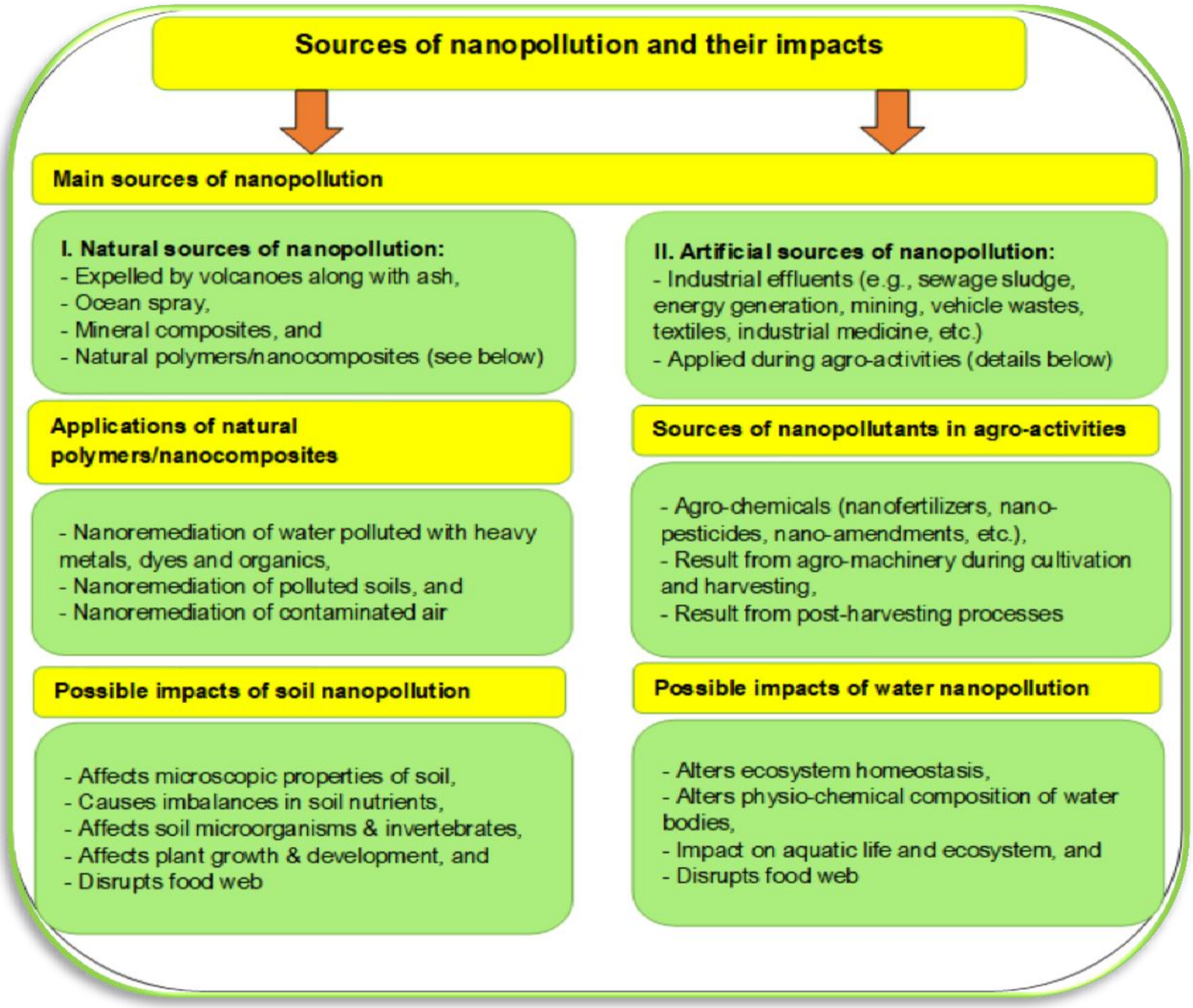

Fig. 3. General impacts and main sources of nano-pollution.

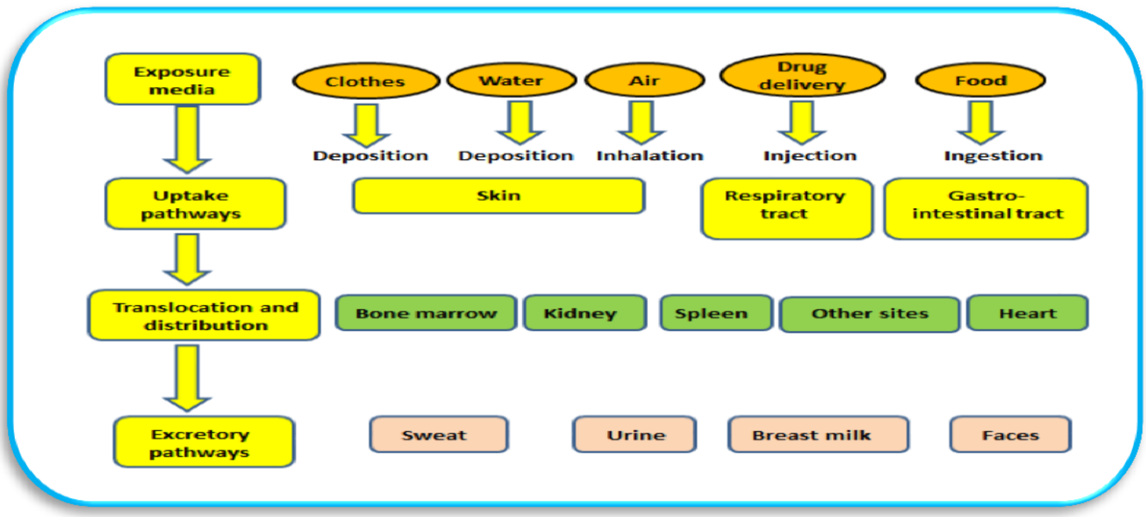

Fig. 4. A summary for the adverse health effects and the possible uptake and translocation pathways of the nanomaterials (adapted from Ganguly et al. 2018).

Table 2. A list of some recent review articles on nanoremediation in different media.

Nanoremediation type	The main findings of the study	Refs.
Environmental nanoremediation	Application of nanomaterials for remediation of water, soil, and air remediation using different nanomaterials of metal, carbon, polymer, and silica	Del Prado-Audelo et al. (2021)
Nano-bioremediation	The current methods of biodegradation of pesticides using different microbes and enzymes through nano-bioremediation in polluted soil	Singh and Saxena (2022)
Sustainable nanoremediation	Nano-based techniques can be used in agro-pollution through nano-sensors to follow pollutants and/or nano-biosurfactants	Boregowda et al. (2022)
Sustainable soil nanoremediation	Nanoremediation using nanomaterials to remediate heavy metals from polluted soil; long-term effects of NPs on soil remediation still need further more investigations	Ahmed et al. (2021a)
In situ nano-remediation of soils	*In situ* nanoremediation of soils and groundwaters, which their development is closely related to economic motive & regulatory issues	Marcon et al. (2021)
Nanoremediation of ground water and soil	Nanoremediation technologies of polluted soil and water using sustainable and advanced approaches for mitigating the eco-toxicity of nano-based approaches such as photocatalysis, nano-sensing etc.	Ganie et al. (2021)
Nano-sensors for eco- monitoring	Using nano-sensors for environmental monitoring of polluted soil with arsenic and mechanisms for removing from soil by nanocomposites	Alidokht et al. (2021)
Nano-photo-remediation	Nano-photocatalyst mediated treatment is a best approach to manage of polluted soil, sediment, and water with organochlorine compounds	El-Sheikh et al. (2021)
Environmental nano-remediation	Nanopollution has perturbed the environment to pose serious health hazards and nanotoxicity to plant, microorganisms and human health	Ahmed et al. (2021b)
Physical nano-remediation	Nano-scale-zero valent iron production using milling method has the best environmental score, but ultrasonic wave method is the worst	Visentin et al. (2021)
Green nanoremediation	Green nanoremediation for cleaner environment using plant extracts, plant wastes, bacteria, fungi, as well as their adaptability and challenges for transitioning from concept to reality for human health	Dutta and Das (2021)
Nano-environmental sustainability	Different applied green nanomaterials should be assessed the environmental risks due to a bio-based nano-synthesis may is not per se a sustainable process	García-Quintero and Palencia (2021)
Nano-catalysts for water treatment	Nano-materials derived from starch, cellulose, pectin, gum, alginate, chitin and chitosan for sustainable water treatment by catalytic degradation of dyes, phenols, nitroarenes, and removing heavy metals	Nasrollahzadeh et al. (2021)
Nanoremediation of textile mill effluents	Effects of textile mill effluents on soil and their remediation approaches (e.g., nanoremediation), which polluted soil as a toxic and their degradation products	Markandeya et al. (2022)
In-situ, and *Ex-situ* nano-remediation	Nano-remediation strategies for polluted soil, water, and air using NPs of Fe-, TiO_2-, based-NPs, dendrimers, silica and carbon nanomaterials, graphene-based NPs, nanotubes, polymers, nanomembranes etc.	Hussain et al. (2022)

soil–water–plant–human (Brevik et al. 2022), and Soil-Human Health-Nexus (Omara et al. 2022). On the other hand, diagrammatic or photographic or pictorial articles are highly effective at communicating these complex nexuses (El-Ramady et al. 2022a, b). Several recent topics have used diagrams or illustrations and/or photographs such as soil and humans (El-Ramady et al. 2022c), management of salt-affected soils (El-Ramady et al. 2022d), the soil–water–plant–human nexus (Brevik et al. 2022), beside other issue like smart agriculture (Abdalla and El-Ramady 2022), the comparison between higher plants and mushrooms (El-Ramady et al. 2022e), nano-farming (Abdalla et al. 2022), and nano-grafting (Bayoumi et al. 2022). The main difference between a typical review article and diagrammatic review is that the pictorial review heavily depends on presenting the available information using diagrams, photographs, and other image-based methods. The fundamental idea of this kind of presentation is that one photo or other image may be better than 1000 words, and therefore a well-illustrated review facilitates communicating the main ideas in the paper (El-Ramady et al. 2022a).

Many health problems are projected to human health under nanopollution (Fig. 2). Although there are several kinds of pollutants, nano-plastic is considered a serious source for human health as reported by many articles (e.g., He et al. 2021; Cárdenas-Alcaide et al. 2022; Huang et al. 2022; Lai et al. 2022; Zhou et al. 2023). Several risks to the ecology and toxicity to humans have been confirmed and associated with nano-plastics (Lai et al. 2022), which their adverse effects on human health could be taken place through uptake and translocation pathways (Fig. 4). Potential exposure routes of nano-plastics and their adverse effects on humans may include potential exposure routes of nano-plastics to humans (i.e., oral intake, air inhalation, and dermal exposure). Nano-pollutants can enter the human body through different routes such as the following sources:

1- Respiratory system: nanopollutants may pass through this system during manufacturing, handling and/or research facilities, aerosols directly applied in nasal or oral cavities; air filters, breathing masks; ambient airborne,

2- Skin: through wound dressings; antibacterial textile (e.g., sheet, towels, socks, underwear, fitness wear); antibacterial surfaces, paints; cosmetic products (e.g., lotions, roll-on deodorants, hair products); computer hardware and mobile devices,

3- Reproductive system: through the contraceptive devices; women's personal hygiene products,

4- Circulatory system: through intravenous injection nano-enabled drugs or drugs delivery or diagnostic system implant, medical catheters, and

5- Gastrointestinal tract: through cooking utensils and coatings or food packaging, health supplements, water filters and oral hygiene products (e.g., toothpaste, toothbrushes) (Kamal et al. 2021).

4. Possible remediation of nan-pollutants in soils

This section focuses on two issues; (1) using nanomaterials to remove, degrade, or convert pollutants into non-toxic materials or compounds; and (2) how to solve the problem of nanopollutants. There are many organic and inorganic pollutants that represent a risk for environment and human health. Consequently, there is an urgent need to evaluate technologies to alleviate environmental NP pollution. Soil nanoremediation is a promising technology to deal with pollutants in soil using engineered nanomaterials to clean up the soil environment. Furthermore, nanoremediation is a sustainable alternative to eliminate emerging pollutants such as pharmaceutics or personal care products (Del Prado-Audelo et al. 2021). Several studies have been published on soil nanoremediation (**Table 2**), whereas there are few studies on nanopollutants (e.g., Ahmed et al. 2021b; Antuña et al. 2022; Das et al. 2022). Several technologies can be applied for soil remediation of heavy metals and other pollutants, including physical remediation (e.g., soil thermal desorption and soil replacement), chemical remediation (e.g., chemical leaching, chemical stabilization, electrokinetic remediation-permeable reactive barrier, and chemical oxidation/reduction), bioremediation including phytoremediation and microbial remediation (Song et al. 2022), as well nanoremediation (**Table 2**) and various combined remediation methods.

Nanomaterials and nanoparticles can have opposing effects in the environment, including soil; they may be used for the nanoremediation of soil pollutants, but they can also be pollutants themselves. Certain mechanisms and many factors control which of these nanomaterials and nanoparticles end up being in the soil. The mechanism of interaction between NPs and plants or soil microorganisms is affected by factors such as plant physiology, microbial activity, the stable nature of nanomaterials, and soil environmental conditions (Ahmed et al. 2021a). The behavior of NPs in soil is greatly influenced by their traits, including physiochemical and morphological constitution, as well as properties affecting the uptake of NPs like functionalizing and coating the NPs surface (de la Rosa et al. 2021). Further investigations are needed to explore the interaction mechanisms between plant-NPs-agroecosystem, which can minimize the negative impacts of soil pollutants like heavy metals in plants as well as in the entire agroecosystem. The interaction between nanopollutants and other pollutants in soil or/and waster is also a very fertile area for research under different conditions like the presence of cultivated plants and/or soil microorganisms.

5. Conclusions and researchable priorities

Recent intensive application of engineered nanomaterials in different areas of our life including agricultural, industrial, and environmental issues has gained enormous attention due to NPs beneficial applications. However, the use of nano-sources in agricultural activities might result in the release of NPs into agroecosystems and may pollute our food supply by entering into the soil-plant-water system. Therefore, NPs interactions with agroecosystems and their potential toxicity in living systems have become a global concern. Several barriers, including safety concerns, and efficient delivery at field scale must be addressed before widespread and final adoption of nanotechnology into agriculture. More information on the long-term toxicological fate of NPs released into the agro-environment and their biodegradation are still required. Soil nano-pollutants have an impact on human health, including direct and indirect effects. Nanomaterials may offer several cost-effective and efficient tools to limit the spread of pollutants in the environment. However, nanomaterials may themselves become powerful pollutants in the environment. The adverse effects of nanopollutants could be reduced using biosynthesis methods rather than physical and chemical methods of NP-synthesis. Effective regulatory measures that ensure high environmental standards are maintained with NPs use are also needed. Several open questions open questions remain regarding nanopollution, which may depend on the type of nanopollutants, their content, the kind of media, different environmental and climatic factors, etc. The possible interactions between nanoparticles and other pollutants in soil or in water is still a great area for investigation.

Conflicts of interest

"There are no conflicts to declare".

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