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The hidden impacts of micro/nanoplastics on soil, crop and human health

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ABSTRACT

This review examines the growing concerns surrounding the ubiquitous prevalence of micro/nanoplastic pollution and the possible dangers and consequences on the global environment. While the environmental effects have been extensively studied, the extent of potential human health hazards and effects remains largely unexplored. This overview aims to shed light on the connection between plastics, human well-being and environment to extend current knowledge on this subject. The review covers the status of global micro/nanoplastics pollution, and the risks they present to human health encompass harmful chemical elements, contaminant carriers, and physical harm. Several key findings emerged: (1) Microplastics in the soil adhered to crop seeds and root surfaces or accumulated within their vascular systems, leading to the obstruction of water and nutrient uptake; (2) micro/nanoplastics induce oxidative damage to plants disrupting their metabolic processes; (3) Chemical additives released from microplastics triggered cytotoxic and genotoxic effects in plants; (4) Microplastics altered the biotic and abiotic conditions of the soil, thereby affecting the availability of water and nutrients to crops; and finally, (5) The combined toxicity of different microplastics in soil can have adverse effects on plants. In conclusion, this review sheds light on the repercussions of soil microplastics on plants and advocates, for further research to better understand their impact on the natural environment and human well-being.

1. Introduction

Plastic pollution has emerged as a burgeoning global crisis, marked by an escalating magnitude and gravity. Spanning from the extraction of raw materials for production to the final disposal of substantial waste, plastics exert a detrimental influence on various environmental realms, the well-being of wildlife, and even the potential health implications for humans, carrying the potential for far-reaching global health and societal repercussions. The pervasive impact of plastics is on an alarming trajectory, set to intensify in tandem with the escalating pace of pollution [1]. With over 8 billion tons of plastic produced since 1950, we are now in a new era: the "plasticocene."Currently, the world produces just under 350 million tons of plastic each year, with a growth rate of 5% annually. Today, more than 80% of produced plastics are thermoplastics formed by polymerizing monomers into high molecular weight chains Niyitanga et al., 2021 [2]. These thermoplastic polymers are then moulded for various uses through processes that modify their physical and chemical properties (e.g., melting, extrusion, pelletization) through the addition of various additives, ranging from antioxidants to plasticizers, clarifiers, colorants, etc., added to confer the desired characteristics, depending on the applications.

It took decades of awareness about sustainable disposal of plastic waste, decades of stories about the consequences of pollution caused by this waste. But pollution from plastics – remnants of bottles, single-use plastics, fishing nets – is just the tip of the iceberg because what truly poisons the planet and all its inhabitants are the tiny particles derived from the degradation and disintegration of plastics, named microplastics (MPs) and nanoplastics (NPs), highly resistant to (bio)degradation that resist in the environment long.

Despite the seriousness of the problem, there is still no regulatory definition for microplastics. According to Regulation (EC) No 1907/2006, also known as the REACH Regulation (Registration, Evaluation, Authorization, and Restriction of Chemicals), microplastics are described as "solid particles composed of polymers, which may contain additives or other substances, with particles having either: (i) dimensions ranging from 1 nm to 5 mm in all directions, or (ii) for fibers, a length between 3 nm and 15 mm and a length-to-diameter ratio exceeding 3."The REACH Regulation does not provide specific

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provisions for nanomaterials. The European Commission adopted the Recommendation on October 18, 2011, stating that " nanomaterial refers to native, secondary, or fabricated substance, comprising particles present in not bound structure, aggregate, or agglomerate, where at least half of the particles in the number size distribution feature one outer dimension within the size range of 1 nm–100 nm.

Currently, the following classification is conventionally recognized for plastic waste in all its possible forms (fragments, fibres/filaments, beads/spheres, film sheets, and pellets):

- Macroplastics (>200 mm)
- Mesoplastics (5–200 mm)
- Microplastics: plastic snippets varying in dimensions from 0.1 μm (micron, i.e., one thousandth of a millimeter, 10-6 m) to 5 mm, including: a. Medium-sized microplastics (1.01–4.75 mm) b. Lesser microplastics (0.33–1.00 mm)
- Nanoplastics: plastic particles ranging in size from 1 nm (0.001 μm) to 100 nm (0.1 μm or millimicron, i.e., one thousandth of a micron; 10-9 m).

Microplastics (MP) can be further classified as:

- Primary microplastics, are small particles released directly into the environment. It is estimated that this category of microplastics accounts for 15–31% of microplastics in the ocean. The main sources, in descending order, are: washing of synthetic textiles (35% of primary microplastics) and subsequent release through wastewater into the environment, and abrasion of tires during driving, with the resulting residues becoming part of the atmospheric particulate matter that we breathe every day (28%); Microplastics intentionally added to body care products (e.g., microbeads added to facial scrubs and exfoliants, toothpaste, paints, abrasive products, etc.) 2%.
- Secondary microplastics, those produced from the degradation of plastics (e.g., bags, bottles, disposable tableware, detergent and soap bottles, fishing nets, etc.). These represent approximately 68–81% of the microplastics present in the oceans and seas. It is not surprising; therefore, which sea salt constitutes a primary food source of secondary microplastics. Whereas microplastics are the result of plastic degradation, they also carry various other pollutants represented by the same additives used in plastics. Of particular importance are certain substances classified as "endocrine disruptors," such as phthalates, used to make plastic more flexible, and Bisphenol A, used to make detergent bottles or some disposable tableware more resistant. In addition, other contaminants potentially adsorbed on the exposed surface, including environmental pollutants, should be considered.

The issue of MP/NP pollution in terrestrial systems received significant attention, especially in recent years. In a publication in Global Change Biology, de Souza Machado et al. [3] identified MP/NP pollution as a stressor capable of inducing global changes in terrestrial systems. The same study analysed the environmental fate of MPs in terrestrial habitats and highlighted significant connections with freshwater systems. The authors analytically discussed the potentially broad-spectrum toxicity of NPs on terrestrial organisms and the potential ecological involvements. The conclusions led to the recognition of the omnipresence of MP/NP in terrestrial environments and the potential and worrisome deleterious consequences on ecosystems and health.

Microplastic pollution was identified as one of the most relevant issues to address in order to ensure global biodiversity conservation. This opinion strongly emphasizes the urgency to develop research aimed at knowing the ambient destiny and effects of these little plastic motes in ground processes. The proposed study hypothesized that out of the over 400 million tons of plastic made worldwide each year, one-third finishes on the mainland and in freshwater, giving rise to MPs and NPs [4]. The research also examined MP pollution in wastewater, highlighting how these particles persist in sewage sludge that is then reused in agriculture, thus facilitating the transfer of thousands of tons of plastic into cultivated soils each year. In addition to this source of soil contamination, agricultural activities themselves generate secondary microplastics from packaging, bottles, mulching nets, irrigation systems, polystyrene containers, greenhouse cover films, etc. Fig. 1 schematically represents the main pathways of MP/NP contamination in agricultural soils [5]. In 2018, a Scientific Opinion of the European Commission [6] was published, drawing attention to the ubiquity of microplastics/nanoplastics (MPs/NPs) in air, sediments, freshwater, soils, animals, food, and water. Drinking water, according to a global average estimate, would contain about 5–6 MP particles per litre, a number that increases over twenty times when the water is contained in plastic bottles. Carbonated drinks, tea, orange juice, tonic water, beer, and so on are not exempt from this contamination. Significant quantities of MP/NP have been detected in sugar and honey.

The above-mentioned facts suggest that terrestrial pollution from MP/NP may be considered higher, more pervasive, and more severe than marine pollution. The enormity of the issue in the marine environment has so far overshadowed the pollution of terrestrial environments, especially agricultural soils, which are a hidden treasure providing the vital sustenance for autotrophic plant species, upon which the life of the heterotrophic human species and the entire animal world are irrevocably dependent.

Scientific evidence has forcefully demonstrated how different the reality is. The study published in 2020 in "Environmental Research" [7] conducted by a group of researchers from the University of Catania's Laboratory of Environmental and Food Hygiene in collaboration with the Laboratory of Biochemistry and Environmental Toxicology in Sousse, Tunisia, found, for the first time, the presence of NP/MP in fruits and greens (apples, pears, lettuce, carrots, broccoli, and potatoes). This represented a true turning point, an explosive element that definitively brought to the forefront of current scientific debate the interaction between the hidden treasure, contamination from NP/MP, and human health. The contours of the problem have now significantly expanded and no longer concern only the general aspects related to ecosystem pollution. The consequences of the discovery of the "insecurity" associated with contamination from microplastics/nanoplastics in plant-based foods are disruptive, as these foods represent the foundation of the Mediterranean diet, which is recognized by UNESCO as an intangible cultural heritage of humanity. This diet used, as reference for the Universal Diet proposed by the EAT-Lancet Commission underlies a healthy lifestyle able to promote longevity and sustainability.

In this distinctive review, we provide a comprehensive examination of the existing literature, delving into the consequences of microplastic (MP) and nanoplastic (NP) pollution on soil, plants, food, and human health. Our objective is to clarify their behaviour and pollution dynamics across diverse environmental contexts, while also illuminating their integration into the food chain and the resulting effects on human well-being.

Furthermore, it discusses the methods for identifying and managing MNPs and evaluates the critical challenges in combatting MNPs in soil, providing prioritized areas for future research studies.

2. Micro/nanoplastic impact on soil

Micro/nanoplastic pollution is a growing concern, particularly for its impact on soils. However, the effects of micro/nanoplastics in soil showed considerable variation, indicating a significant dependence on contextual factors (Fig. 2). To achieve a deeper comprehension of the circumstances influencing micro/nanoplastic-related impacts, the examination of the influences of MNPs form, kind of polymer and incubation period on soil properties have been highlighted in this review.

Soil can be considered the primary reservoir of MNPs, surpassing the aquatic environment in terms of storage capacity. Plastics have the ability to mix with soil aggregates, leading to long-term retention. the

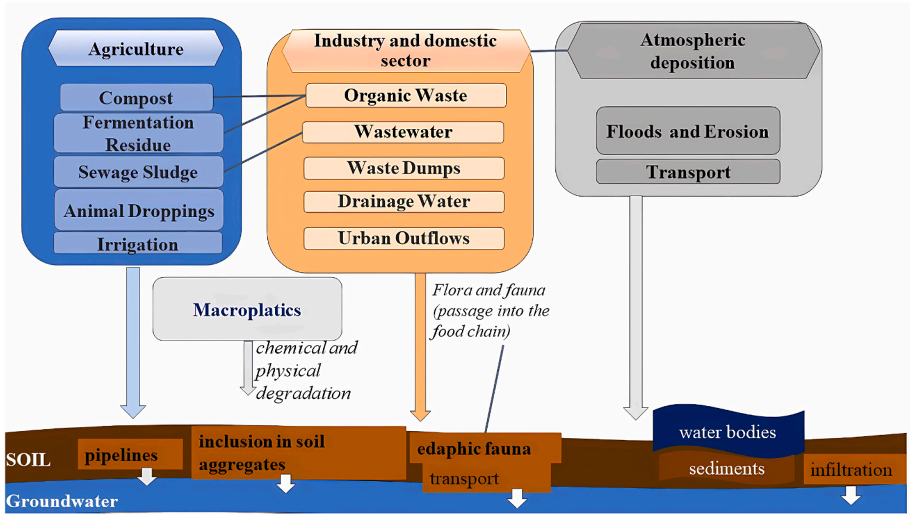

Fig. 1. This schematic illustration outlines the primary pathways of microplastic (MP) and nanoplastic (NP) contamination in agricultural soils. MP/NP originate from different sources and make their way to the soil and subsequently infiltrate aquifers.

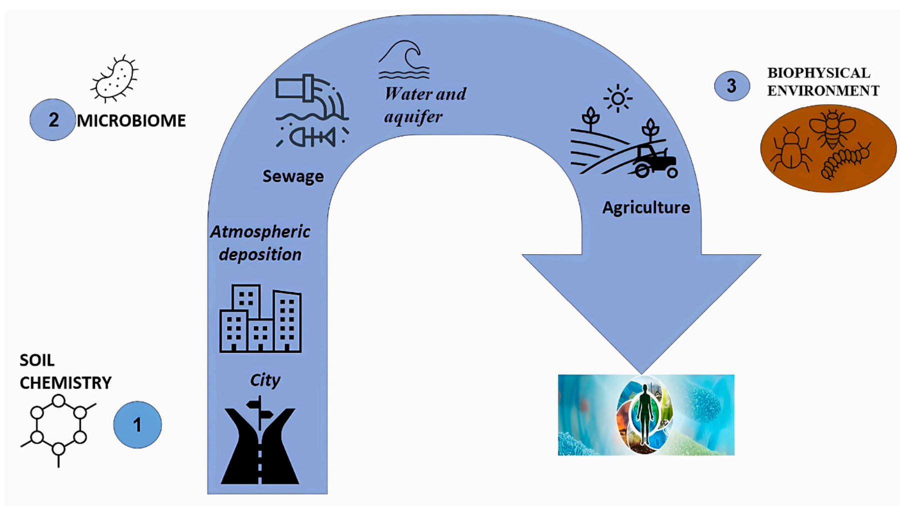

Fig. 2. Micro and nanoplastics (MNPs) find their way into the soil through storage, translocation, erosion, degradation, and leaching, permeating deeper soil layers. Micro and nanoplastics movement raises the risk of groundwater contamination and introduces the possibility of entering plants and subsequently the food chain.

fate processes of MNPs in soil involve storage, movement, erosion, degradation, and leaching into groundwater [8] (Fig. 2). MNPs with higher densities exhibit a tendency to persist in the soil, migrating towards deeper layers, potentially contaminating groundwater, and entering plants and food chain. Conversely, MNPs with less densities tend to remain at the surface and may be transported by wind and water erosion [9] contaminating more distant soils. Over time, MNPs can become buried for factors such as floods, accumulation, and other processes, thereby contributing to their preservation. While soil characteristics, such as microbial communities and pH, can influence the safeguard process, specific practices like tilling can resurface buried particles. It is estimated that MNPs are present in European or American farmlands approximately, in a range, of 63.000–430.000 tons, originating also from the adjunct of fertilizers such as composts and sewage sludge (not analysed for plastic content), as well as the weathering of plastic mulch.

The presence of microplastics appears to increase the nutrient content of dissolved organic matter (DOM) in soil, including carbon, nitrogen, and phosphorus. This suggests that microplastics may contribute to the piling of organic compounds and nutrients in soil [10]. Microplastics may significantly affect the composition of DOM in soil. They can increase the concentration of aromatic substances and carbohydrates in the dissolved organic matter [11]. As reported by Meng et al. [12] microplastics seemed to stimulate microbial activity in soil. This increased microbial activity may result in elevated extracellular enzyme activity, indicating an enhanced decomposition and conversion of organic compounds in the soil.

The chemical arrangement of MNPs, including their molecular chain position and functional groups, can influence their ability to adsorb other substances like heavy metals or antibiotics [13]. Consequently, this interaction can impact soil properties and microbial activities [14]. For instance, polyethylene (PE) has been shown to possess elevated sorption capacity for phenanthrene, and its nitrogen heterocyclic analogues, which can impede microbial activities in soil [15]. Moreover, researches revealed which various kind of polymers, such as PE, PP, and PVC, might display diverse capabilities of sorption for specific chemicals [16–18].

Plastic pollution is a pressing global environmental issue, and the presence of plastics in soil can have far-reaching ecological implications, giving rise to the formation of a plastisphere within the soil ecosystem"

[19]. Plastics that are present in soil, such as polyethylene, polypropylene, and polyvinyl chloride, serve as substrates for microbial colonization. Bacteria, fungi, and other microorganisms can attach to and colonize the plastic surfaces, forming a unique microbial community known as the plastisphere [20]. The composition of the plastisphere microbial community can vary depending on factors like the type of plastic, environmental conditions, and the duration of exposure. Some microorganisms can degrade or modify the plastic, while others may interact with the plastic in different ways. While not all microorganisms can break down plastics, some have the capability to degrade certain types of plastics. For example, some bacteria like *Pseudomonas and Ideonella sakaiensis* have been discovered with the ability to break down polyethylene and polyethylene terephthalate (PET), respectively. The presence of plastics and the development of the plastisphere in soil can have various ecological implications.

Understanding, of the effects of MNPs on soil respiration is still in its initial phases. Soil respiration, acting as an index of total soil microbial activity [21], exhibits high sensitivity to soil texture, porosity, moisture, and pH [22]. These soil properties have the potential to be influenced by the addition of MNPs [23–25]. Recently, studies have suggested that MNPs can directly or indirectly affect the soil microbial community [26, 27], consequently influencing soil respiration [25,28]. Microplastics can also influence the composition and diversity of soil microbial communities, inducing alterations in the variety and prevalence of various microbial species. Some microbes may thrive in the presence of microplastics, while others may be negatively affected or even suppressed. Enzymes produced by soil microbes, play a crucial part in the breakdown and decomposition of organic matter. Microplastic pollution can alter the activity of these enzymes, potentially leading to changes in the rates of organic matter decomposition and nutrient cycling in the soil. Liang et al. [29] studied the impacts of microplastic fibers by conducting a soil incubation experiment, examining how changed the quantity of water-stable aggregates (WSA) and the activities of β-glucosidase, β-D-celluliosidase, N-acetyl-b-glucosaminidase, phosphatase enzymes, with or without organic materials. Data evidenced that organic matter influenced the effects of microplastic fibers on soil aggregation and enzyme activities. Other authors evidenced also that MNPs have the ability to make changes in soil microbial communities [27,30–32], influencing as consequence soil enzymatic activities [33]. Lin et al. [34], in their microplastic manipulation experiment, where low-density polyethylene fragments were added in the field, discovered significant impacts on the constitution and richness of microarthropod and nematode communities. Surprisingly, they observed only minimal microplastic consequences on the amount of soil microbial communities. The results on how MNPs influence soil microbiota are recent and vary significantly amidst the studies that have been documented. Ya et al. (2022) [35] observed significant changes in the diversity and abundance of soil microbial communities when exposed to polyethylene (PE) and polypropylene (PP). Specifically, they found an increase in the abundance of *Acidobacteria* and *Bacteroidetes*, while *Deinococcus thermus* and *Chloroflexi* diminished concomitantly. Koroleva et al. [36] showed that cellulose acetate, MNP contained in the cigarette butt filters, exerted a substantial influence on the biodiversity of soil bacterial communities, highlighting that various types of MNPs can elicit diverse effects on soil microbiota. De Souza Machado et al. [3] observed that polyamide and polyethylene led to a notable increase in microbial activity, whereas polyester and polymethyl methacrylate decreased microbial activity. MNPs can support microbe's survival even under unfavorable conditions through the formation of biofilm layers [37]. Nevertheless, this defensive mechanism can inadvertently create an environment suitable for the diffusion of pathogenic and potentially harmful microorganisms [38]. On the contrary, several studies found no significative effect of MNPs on soil microbiota [26,31,39]. Nevertheless, additional research has emphasized the adverse influence of MNPs on microbial processes, particularly their inhibitory effect on the degradation of soil antibiotics and specific antibiotic resistance genes [40,41]. These adverse effects have been extended to soil enzymes such as urease, glucosidase, and phosphatase. Yu et al. [42] found that microplastics concur with soil microorganisms for physicochemical niches, resulting in a reduction in microbial activity and, consequently, a decrease in extracellular enzyme activity. Interestingly, the impact of MPs exposure on enzyme activities varied among different aggregate-size fractions. Each fraction exhibited divergent responses to the presence of MPs, highlighting the intricate nature of the interplay between microplastics and soil microbial communities. The microplastic form and polymer type may also have a pivotal role on soil enzyme activities. Polyethylene and polyvinyl chloride microplastics exerted varying effects on enzyme activity. For instance, they have been found to raise enzymes like urease and acid phosphatase [26,27]. On the other hand, polypropylene, polyester, and PVC may either inhibit or enhance soil fluorescein diacetate hydrolase activity, in respect to the specific polymer type [10, 3, 43, 278.

Additionally, microplastics could negatively impact enzymes involved in cellulose degradation, such as β-D-glucosidase and cellobiosidase, as well as enzymes related to chitin and phosphorus cycling, like N-acetyl-β-glucosaminidase and phosphatase, respectively [28,29]. Additionally, to what previously written on the effects of MNPs on soil microorganisms, soil biota, both microorganisms and soil invertebrates have a central role in the transformation and degradation of micro- and nanoplastics (MNPs). For instance, *Bacillus*'s strain 27 and *Rhodococcus*'s strain 36, native to mangrove sediments, caused weight losses of 4.0% and 6.40%, respectively, in polypropylene (PP) MPs after 40 days of incubation [44]. Other microbial species, including *Paenibacillus* [45] *Pseudomonas, Bacillus, Brevibacillus, Cellulosimicrobium, Lysinibacillus, and Aspergillus flavus* [46], have also been recognized as possible agents for the degradation of MNPs. After 60 days of incubation in a non-carbonaceous basal medium inoculated with *Paenibacillus*, the dry weight of polyethylene (PE) exhibited a reduction of 14.70%. Fungal species are efficiently MNPs degraders for their ability to adhere to or go inside the particles and favor degradation by forming chemical bonds (such as carbonyl, carboxyl, and ester groups), ultimately reducing their hydrophobicity. Moreover, MNPs can be modified by specific microbial enzymes. Yu et al. [42], Zhou et al. [47], Lozano et al. and Salam et al. [28,48] indicated that MNPs can potentially influence the availability of nutrients and substrates, possibly for the absorption of microplastics or competition with microorganisms for physicochemical niches [42]. Recently, Li et al. [49] observed a slight reduction in vegetable biomass when higher concentrations of PF-MPs were present, suggesting a potential negative impact of elevated PF-MP levels on crop growth. The presence of PF-MPs seems to have affected soil microbial communities, which may be associated with the decrease in vegetable biomass. However, further details are required to determine the specific nature of these changes. Notably, a positive correlation was found between the diversity of micro-eukaryotic communities and vegetable biomass, indicating that a more diverse micro-eukaryotic community could benefit crop growth. It should be noted that micro-eukaryotes encompass various organisms, including fungi and algae. Similarly, the functional diversity of bacterial communities exhibited a positive relationship with vegetable biomass, suggesting that greater functional diversity among bacteria may be linked to improved crop growth. Functional diversity refers to the range of roles and functions performed by different bacterial species within the community [49,50]. In conclusion, data reported above are controversial and showed that micro- and nanoplastics (MNPs) can have both positive and negative effects on the physical/chemical properties of soil, soil microflora, and invertebrates. Additionally, some studies have found no significant effects of MNPs in these contexts. The diverse effects of MNPs on abiotic and biotic factors can be ascribed to the considerable variability of experimental circumstances among different studies. Factors such as the type and dosage of MNPs, soil types, and incubation time can profoundly influence the observed outcomes.

3. Micro/nanoplastic effects on plants

The brief review of scientific literature from the past five years confirmed and demonstrated that plants are capable of absorbing microplastics and nanoplastics present in agricultural soils (Fig. 3). In spite of the widespread presence of MP in the terrestrial environment, the absorption by cultivated plants was initially overlooked as it was supposed that these plastic particles were too big to cross the physical barriers of uninjured plant tissues. However, a study conducted by a team of researchers [51] from the Chinese Academy of Sciences refuted this assumption, demonstrating that MP can indeed penetrate plant tissues and contaminate plant species. It was already known that particles of about 50 nm in size could penetrate plant roots, but the study demonstrated that particles about 40 times larger can also penetrate plants through the root system (Fig. 4). The research team used submicron and micrometer-sized spherical particles of polystyrene and polymethyl methacrylate with minimal mechanical flexibility, showing how these particles were able to penetrate the small apoplastic space in plant root cells. The study also illustrated the absorption mechanism related to the presence of small cracks on the lateral roots, which provide an additional pathway for the access of both MP and NP into the xylem vessels. Furthermore, the vital cellular scission occurring in green radicles, such as the meristematic zone in the root tip, can facilitate the influx of microplastics (MPs). For instance, Polystyrene motes can infiltrate the stele entering across crack sites during the development of early side radicles [51], pointing out that MNPs can amass in roots through root damages elicited by below-ground herbivores, and wound. MPs that infiltrate, through incomplete Casparian strips during root development, can be shifted to the above-ground part of the plant through the apoplast path along the cell walls of the vascular bundle. Moreover, plant pathogens, causing damage to the root tissues, make easy the entry of MNPs heightening their toxicity. It has been observed that PS MNPs can be present in the vascular systems, such as the xylem of roots and stems, as well as leaf veins, and can aggregate on cell walls [51], suggesting the apoplastic movement of MNPs within plant tissues. Additionally, it was found that higher transpiration rates promote particle absorption, this emphasizes transpiration as the primary driving force behind their movement. Furthermore, it has been observed that leaves can uptake MNPs and move them downward to the roots [52].

Lian et al. [53], studied how polyurethane MPs (PU MPs) acted on two cultivars of maize (*Zea mays*). Their data showed that in the treatment with 1% PU MPs, there was no significative modification in the height of one maize cultivar (ZNT 488), while there was a meaningful enhancement in the height of the other cultivar (ZTN 182) in respect to the control. These findings suggest that PU MPs did not cause widespread phytotoxicity but rather promoted the growth of the ZTN 182 cultivar.

Wu et al. [54]. conducted an experiment with polystyrene MPs (PS MPs) and studied their effects on two subspecies of rice (*Oryza sativa*). The results showed contrasting effects between the two subspecies. The Y900 plants exhibited a 10.62% reduction in yield, while the XS123 plants showed a 6.35% increase in yield when exposed to PS MPs. The study also found that metabolite accumulation and energy expenditure paths were repressed in Y900 grains but stimulated in XS123 grains. Gene expression related to the tricarboxylic acid cycle was also diminished in Y900 grains but increased in XS123 grains. Based on these findings, the authors deduced that the XS123 subspecies responded better to the effects of MP exposure compared to the Y900 subspecies.

However, the specific mechanisms by which MNPs enter, transport, and redistribute within plants need still further insights. Recent studies evidenced also that MNPs can adhere to seed and root surfaces, for their small size and high adsorption capacity, hindering seed germination, root elongation, water and nutrient absorption, inhibiting, in the end, plant growth. The attachment and build-up of MNPs can trigger oxidative stress, cytotoxicity, and genotoxicity in plants, leading to various alterations in plant growth, mineral nutrition, photosynthesis, toxic accumulation, and plant tissue metabolites. The phytotoxicity of MNPs varies depending on their polymer type, size, dose, and shape, as well as plant tolerance and exposure conditions. Due to their various sources and persistent nature, micro- and nanoplastics are found ubiquitously in the atmosphere [55,56]. As a result, via atmospheric deposition, MNPs are expected to reach and adhere to the aerial parts of plants, especially leaves. A study revealed that microplastics (MPs) comprise approximately 28% of the total substances attached to leaves, underscoring the importance of terrestrial plants as a temporary sink for atmospheric MNPs [57]. The stomatal pathway is commonly regarded as the exclusive route for the entry of nanoparticles into leaves [58]. Lian et al. [59] were the pioneers in illustrating the absorption of polystyrene nanoparticles by lettuce leaves via stomata, and subsequent downward movement to the roots. The response of plants to MNPs generally varies depending on the type, size, dose, and shape of the MNPs. Polystyrene (PS) at low concentrations or with small sizes (within the range of 25–150 μm) decreased the green mass of Chinese cabbage, while high-density polyethylene (HDPE) of the same dose and size did not show significant effects [60]. Cucurbita pepo L. exhibited smaller leaves with reduced lamina, when treated with PVC and PP of small sizes

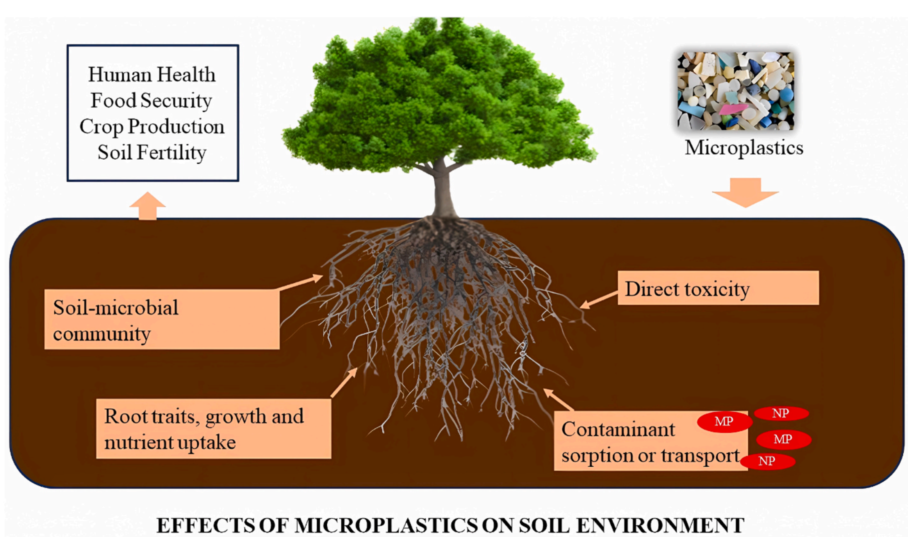

Fig. 3. The interactions between micro and nanoplastics with terrestrial photosynthetic organisms. Micro and Nano Plastics come into contact with plant roots, affect the structural integrity of root cells, consequently impact the uptake and transportation of essential nutrients.

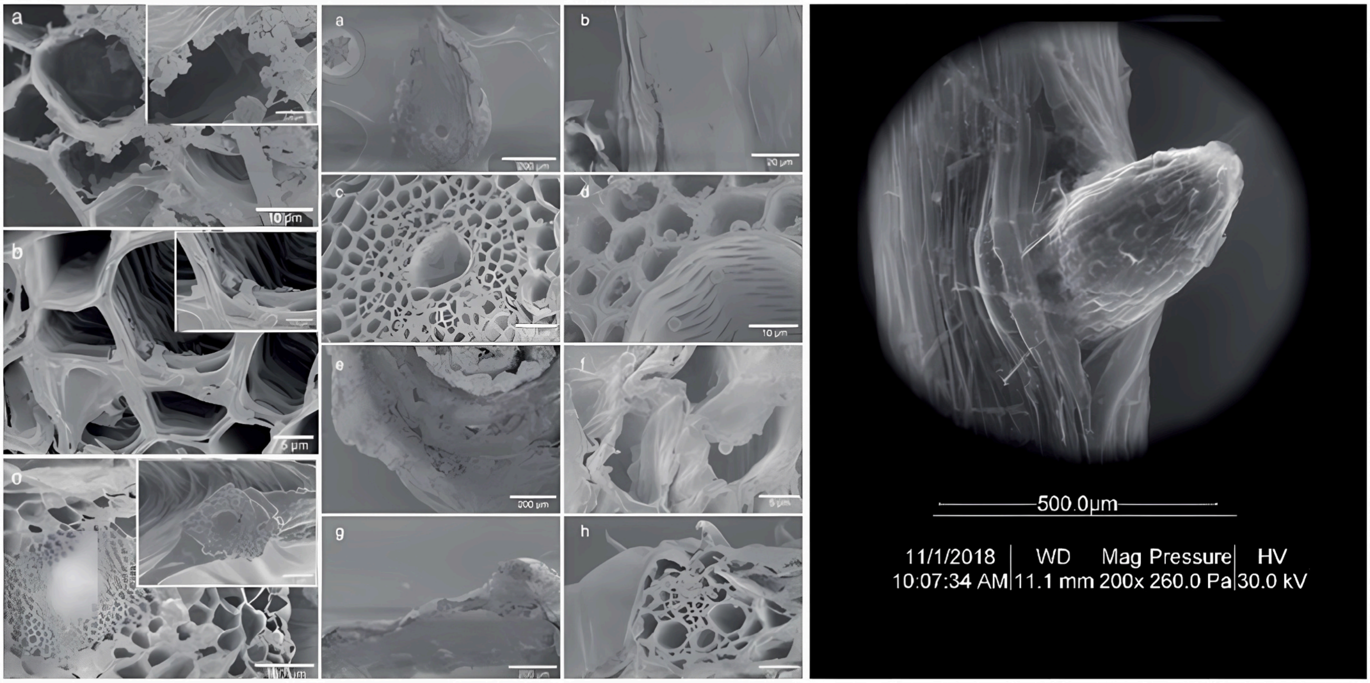

Fig. 4. Micro- and nano-plastics possess the capability to infiltrate plants by traversing the apoplastic space within the root cells (source: Li et al.) [93].

(40–50 μm) [61]. The accumulation of MNPs and resulting harm in plants can additionally influence yield of cultures, safeness and quality of food, posing possible health hazards. An expanding collection of proofs indicates that nanoparticles (NPs) can have toxic effects on plants. An usual response of plants to abiotic stress factors is the accumulation of reactive oxygen species (ROS). ROS molecules play a dual role in cellular signalling and gene expression regulation. However, excessive ROS levels can conduct to oxidation and damage of numerous components of the cells. The oxidative status of plants is determined by the interplay between the production of ROS and the efficiency of their scavenging by the antioxidant system. Previously, reactive oxygen species were considered to be solely damaging agents, causing oxidation and impairment of biomolecules such as lipids, proteins, and nucleic acids, but recently it is widely recognized that ROS play a crucial role in cell function, as they act as important signalling molecules involved in the regulation of gene expression, developmental processes, and stress responses. It is understood that a certain level of ROS is necessary for proper cellular functioning and that they serve as important signalling elements in various physiological processes. The majority of the studies demonstrated an increase in reactive oxygen species levels and enhanced lipid peroxidation in response to NP exposure. These findings suggest that NP exposure generally leads to oxidative stress in plants. However, it is important to note that there also exist other reports showcasing contradictory results, indicating that the effects of NP on ROS levels and lipid peroxidation may vary based on specific experimental conditions, NP characteristics, and plant species studied. In conclusion, further research is needed to fully understand the complex interactions between NPs and plant oxidative stress responses.

The study conducted by Esterhuizen et al. [62] examined the effects of high-density polyethylene (HDPE) soda bottle cap debris on *L. multiflorum* (presumably referring to the plant species *Lolium multiflorum*). The study investigated different treatments, including new microplastics (MPs), artificially aged MPs, and naturally aged MPs collected from two different locations with varying climates: Lahti (Finland, cooler climate) and Gqeberha (South Africa, warmer climate).

The results indicated adverse effects on germination and growth when exposed to new MPs and Lahti-collected MPs. This suggests that these particular types of MPs had detrimental effects on the plant species. However, artificially aged MPs and Gqeberha-collected MPs showed similar results to the control group, indicating no significant adverse effects on germination and growth.

The study conducted by Mehmood et al. [63] investigated the degradation of polyethylene (PE) and its effect on the growth of *Lactuca sativa* (lettuce). The researchers examined the effects of nitric acid treatment, starch addition, and the presence of *Pseudomonas aeruginosa* bacteria on the degradation of PE and its influence on the physiological and biochemical parameters of lettuce.

The results showed that untreated PE significantly affected the plants, as evidenced by a 45% decrease in leaf chlorophyll content and a 40% reduction in relative water content. These findings indicate that the presence of PE had detrimental effects on the growth and water balance of lettuce.

The study also found that nitric acid treatment was effective in degrading the PE, but it was also phytotoxic, meaning it caused harm to the plants. However, the inoculation of *Pseudomonas aeruginosa* bacteria and the addition of starch reduced the adverse effect of the PE-induced stress and improved the growth of lettuce. These treatments positively influenced various physiological and biochemical parameters in the plants.

Photosynthetic organisms, as well as plants and algae, interact with Metal and Metalloid Nanoparticles (MNPs) in various ways depending on the specific conditions and environment in which they grow. MNPs can affect photosynthesis directly by attaching to the organisms and interfering with their photosynthetic processes. A study by Wu et al. [9] demonstrated that MNPs can directly attach to photosynthetic organisms and disrupt their photosynthetic machinery, leading to reduced photosynthetic efficiency.

Additionally, MNPs can indirectly impact photosynthetic organisms by co-loading with other pollutants present in the environment. This co-loading of MNPs with other pollutants can change the bioavailability and toxicity of these pollutants, thereby influencing photosynthesis in the organisms. Studies by Zhang et al. [64], as well as Dong et al., in 2020 and 2021 [65,66], showed that MNPs can interact with and modify the behaviour of other pollutants, affecting their uptake, transport, and toxicity in photosynthetic organisms. These altered properties of co-loaded pollutants can have consequences on the physiological processes, including photosynthesis, in the organisms.

Deng et al. [67] studied the effect of differing humidity levels and light spectrum intensity on plant development in soil enriched with polyethersulfone (PES) fibers, which are a type of microplastic. The experiment was carried out under simulated continental temperate monsoon climate conditions.

The results of the study showed that the presence of microplastics increased shoot and root biomass in the tested plant species, which included *Bidens bipinnata, Plantago asiatica, Medicago sativa*, *Gynura longituba*, and *Gynura parviflora*. However, the positive effects of microplastics on biomass were reduced under dry conditions, indicating that moisture availability played a role in mediating the relationship between microplastics and plant growth.

The effects of spectral irradiance (specifically, wavelengths above 280 nm and above 315 nm) on plant growth varied depending on the plant species. This suggested that different plant species may respond differently to the specific light conditions.

Nayab et al. [68], assessed the combined effects of microplastics and warming on the growth of *Zea mays* (maize). The study evidenced that the negative impact of microplastics on maize growth were more pronounced under warming temperature conditions of 25 °C, whereas fewer effects were observed under higher temperatures of 30 °C. This indicates that high temperatures may have a greater influence on plant health and potentially overshadow the harmful effects of microplastics.

Furthermore, the research revealed specific thermal stress adaptation mechanisms in maize, including reduced chlorophyll content and stunted growth. These mechanisms may help the plants adapt and respond to the combined stress of microplastics and warming.

These studies provided insights into the complex interactions between microplastics and plant growth under specific environmental conditions. However, the responses can vary depending on factors such as plant species, microplastic type, concentrations, and other environmental factors. Ulterior researches need to understand the mechanisms underlying these effects and their broader implications for plant health and ecosystem functioning.

Several studies investigated the effects of microplastic pollution on different crop species and how certain factors, such as elevated CO_2 levels, acid rain, and the addition of amendments like biochar and compost, can influence the outcomes. Xu et al. [69] evidenced that elevated CO_2 levels enhanced *Oryza sativa* (rice) photosynthesis but reduced nitrogen-fixing bacteria populations. The interaction between microplastic pollution and increased CO_2 levels exacerbated adverse impacts on rice performance, leading to reduced stomatal conductance, transpiration rate, element uptake, and alterations in bacterial amino acid metabolism.

Pignattelli et al. [70] showed that PET microplastics and simulated acid rain had different impacts on *Lactuca sativa* (lettuce). Shoots were more damaged by acid rain, while roots were more affected by the size range of microplastics.

Ren et al. [71]. highlighted that microplastics from wastewater irrigation and sewage sludge use, utilizing degradable mulching film (DMF) and PS beads had contrasting effects on wheat growth. DMF alone diminished wheat plant height and base diameter, but when combined with PS beads (70 nm), enhanced plant height and aboveground biomass. Zheng et al. [72] showed that biochar from wheat straw did not affect *Oryza sativa* yield, but the microplastics carried to a significative decrease in yield. However, the concomitant use of microplastics and biochar diminished these reductions.

Feng et al. [73] put in light as hydrochar from wheat straw diminished ammonia volatilization in wheat soils. The addition of PAN microplastics with hydrochar weakened this effect, while the addition of PE microplastics with hydrochar had no significative impact. Biochar from date nuclei (500 °C) diminished the impact of microplastics on fava bean properties such as enzymes, chlorophyll, and root dry weight and mitigated abnormalities in root tip cells.

The environment in which photosynthetic organisms grow is crucial in determining how they come into contact with MNPs. The presence and concentration of MNPs in the environment can depend on various factors such as industrial activities, pollution sources, and natural processes. The physical and chemical properties of the environment, including pH, temperature, and the presence of other substances, can influence the behaviour and fate of MNPs. Consequently, photosynthetic organisms may be exposed to MNPs through various routes, such as direct contact with MNP-contaminated water or soil, uptake from the surrounding medium, or through interactions with other organisms that serve as vectors for MNPs. In summary, MNPs can interact with photoautotrophs (photosynthetic organisms) both directly and indirectly, affecting their photosynthetic processes. The specific mode of interaction and the extent of impact depend on factors such as the attachment of MNPs to the organisms, co-loading with other pollutants, and the environmental conditions in which the organisms grow. Understanding these interactions is essential for assessing the potential risks and ecological consequences associated with the presence of MNPs in natural ecosystems. Current studies investigating the influence of MNPs on the growth of terrestrial plants often focus on grain crops like corn and wheat, as well as cash crops such as lettuce and cucumber. This emphasis on these particular plant species can be attributed to several factors:

- Economic importance: Grain crops and cash crops are economically significant due to their widespread cultivation and consumption. Understanding the effects of MNPs on these crops is crucial for assessing potential impacts on food production, quality, and safety.
- Agronomic relevance: Grain crops and cash crops are commonly grown in agricultural systems and are subject to various environmental stressors, including pollution. Examining the interaction between MNPs and these crops helps evaluate their tolerance, resilience, and potential effects on crop yield and quality.
- Experimental feasibility: Studying MNPs' influence on plant growth requires controlled experiments, which can be more easily conducted with economically important crops due to their availability, feasibility of cultivation, and established research methodologies.

Indeed, several studies have reported inhibitory effects of MNPs on pigment content in terrestrial photoautotrophs, while others have shown increased pigment content. The influence of MNPs on pigment content can change depending on factors such as MNP type, concentration, exposure duration, and plant species studied. For instance, Wang et al. [74] demonstrated that microplastics (MPs) composed of polylactic acid (PLA) at different soil concentrations (0.1%, 1%, and 10%) reduced the chlorophyll content in maize leaves. The presence of PLA MPs in the soil led to a decrease in the amount of chlorophyll, suggesting an inhibitory effect on photosynthetic pigments. Similarly, Meng et al. [75] found that exposure to low-density polyethylene (LDPE) resulted in a significant reduction in the relative chlorophyll content of common bean leaves (*Phaseolus vulgaris* L.). This study indicated that LDPE, another type of plastic, negatively affected the pigment content in the leaves of terrestrial plants. Conversely, other studies evidenced an increase in pigment content in the leaves of terrestrial photoautotrophs following exposure to MNPs. Sun et al. [40] demonstrated that silver nanoparticles (AgNPs) increased the chlorophyll content in wheat plants, suggesting a stimulatory effect on pigment synthesis. It's important to note that the specific mechanisms underlying the effects of MNPs on pigment content in plants are complex and can involve multiple factors. MNPs can directly interact with plant cells, influencing physiological processes such as pigment synthesis, photosynthetic efficiency, and antioxidant defence systems. Additionally, indirect effects mediated through alterations in soil properties, nutrient availability, or hormonal balance can also impact pigment content in plants. Overall, the influence of MNPs on pigment content in terrestrial photoautotrophs is a complex area of research, and the results can vary depending on various factors. More researches need to elucidate the underlying mechanisms and understand the specific conditions under which MNPs may exhibit inhibitory or stimulatory effects on pigment content in different plant species. Within terrestrial ecosystems, MNPs can impact the photosynthesis of photosynthetic organisms through various indirect mechanisms. While direct interactions between MNPs and leaf cells may be minimal, their interactions with plant roots can have cascading effects on photosynthetic processes. Fig. 3 illustrates these interactions between MNPs and terrestrial photosynthetic organisms. When MNPs in the soil come into contact with plant roots, they can influence the structural integrity of root cells and the uptake and transport of nutrients. These effects can extend to gene expression and signal transduction pathways within the plant. In response to external stimuli, plants may activate stress response mechanisms that can affect normal cellular activities, including photosynthesis. Consequently, parameters such as photosynthetic pigment content, intercellular carbon dioxide concentration, stomatal conductance, and other relevant factors may undergo alterations. Plants possess self-regulation abilities to cope with stressors. For instance, when exposed to MNPs that reduce chlorophyll content, plants may increase leaf area as a compensatory mechanism to mitigate negative impacts. Recent research, like the study mentioned by An et al. [76], has indicated that the adsorption effects of MNPs on plant roots can vary depending on MNP concentration. Higher concentrations of MNPs tend to promote agglomeration, reducing their adsorption by roots and potentially alleviating photosynthetic stress. However, ongoing debates exist regarding whether MNPs can penetrate and be transported within plants through root cells. The ability of MNPs to penetrate plant tissues and directly impact plant growth and photosynthesis remains an active area of research and scientific inquiry. Furthermore, the coexistence of other pollutants in the soil introduces additional complexity. Various substances, including heavy metals, persistent organic pollutants (POPs), nutrients, and microbes, can interact with MNPs, altering their toxicity and bioavailability. These interactions between MNPs and other substances in the soil can modulate their effects on plant physiology and photosynthesis. In conclusion, MNPs can indirectly influence the photosynthesis of terrestrial photosynthetic organisms through interactions with plant roots, which, in turn, affect nutrient uptake, gene expression, and stress responses. However, the entry and transport of MNPs within plants, as well as their interactions with other soil pollutants, are still areas of active research and require further investigation to fully understand their implications for plant growth and photosynthesis. An important issue is the interrelationship between soil, plants, and food security. Plastic pollution can cascade through the soil-plant relationship, ultimately affecting food security. Below is a comprehensive overview of the effects of plastic on the interrelationship between soil, plants, and food security. The incorporation of microplastics into the soil can modify soil structure and porosity. This alteration affects water movement and retention, which is crucial for plant health. Plastics influencing soil microbial community can influence nutrient cycling and soil fertility, crucial for plant growth and development. Some studies suggested that plastics, especially in the form of microplastics, can reduce seed germination rates and impede plant growth. During the degradation process, plastics release various chemicals, including additives like phthalates or bisphenol A (BPA) toxic to plants and disruptive for the hormonal activity. There's scientific evidence that plants can uptake microplastics through their roots, impacting plant health and physiology. The combined effects of altered soil structure, reduced germination, and plant toxicity can lead to decreased crop yields. Lower yields can impact local and global food supplies. Additionally, the uptake of microplastics and associated chemicals by plants poses a risk to food safety. Consuming such contaminated plants can have serious health implications. Over time, the change in microbial communities and reduced organic matter decomposition due to plastics reduce soil fertility, necessitating increased fertilizer use. This can increase the cost of crop production and affect long-term sustainability. Changes in soil structure due to plastic pollution can alter water use efficiency. In regions where water is scarce, this can have significant implications for irrigation and crop health. Microplastics and their associated toxins can move up the food chain. If herbivores consume contaminated plants, these pollutants can then be passed up to higher trophic levels, including humans. As plastics alter soil and plant health, there can be cascading effects on the broader ecosystem, potentially leading to biodiversity loss. The interrelationship between soil, plants, and food security is delicate, and the introduction of plastic pollutants can disrupt this balance in various ways. Addressing plastic pollution in soils is not just an environmental concern but also crucial for ensuring global food security and safety [77].

4. Effect of MNPs on food chain and human health

MNPs are prevalent in terrestrial environments and their interactions with plants are thus inevitable. Plants, are primary producers with a crucial role in the terrestrial food web, representing the link between soil, animal and human. Conti et al. [7] looked into the existence of MNPs in tissues of edible fruits (such as apple and European pear) and vegetables (including lettuce, broccoli, carrot, and potato) obtained from local markets in Catania, Italy. The study evidenced mean concentrations of MPs (microplastics) in the range of 1–4 μm in fruits and vegetables, which were approximately 190.000–196.000 particles/g fresh weight (fw) and 51.000–126.000 particles/g fw, respectively. This study evidenced MNP accumulation in edible plant tissues obtained from real-world market sources. In laboratory settings, the uptake of MNPs by plant roots and their subsequent acropetal transport within the plants have been well-described for various plant species. These species include lettuce, carrot, cucumber, onion, wheat, rice, maize, bean, and thale cress (*Arabidopsis thaliana*), the majority of which are edible crops. These studies demonstrated that MNPs can be taken up by plant roots and transported to other plant tissues, including shoots and leaves. The accumulation of MNPs in edible plant parts raises concerns about the potential human exposure to MNPs through the consumption of contaminated crops (Fig. 5). Overall, while evidence regarding the accumulation of MNPs in plants from field settings is still emerging, laboratory studies confirmed the uptake and transport of MNPs in various plant species, including edible crops.

If MNPs are incorporated into plant tissues, they may be transferred to herbivorous organisms, such as insects or grazing animals, through the food chain. This transfer can occur when herbivores consume plants containing MNPs. MNPs that enter the animal system through the food chain can accumulate in animal tissues. This accumulation may depend on factors such as the concentration and size of MNPs, the frequency of exposure, and the metabolic processes within the animals. The long-term effects of MNP accumulation in animal tissues are still being investigated. MNPs have the potential to bioaccumulate in organisms and bio-magnify as they move up the food chain. This means that MNPs could become increasingly concentrated in higher trophic levels, potentially leading to elevated exposures and impacts on organisms at the top of the food chain (Fig. 5). It is worth mentioning that the effects of MNPs on the food chain can vary depending on several factors, including MNP characteristics (size, surface coating, composition), exposure levels, and the specific organisms and ecosystems involved. Additional research is necessary to comprehensively grasp the potential hazards and advantages linked to the implementation of MNPs (Magnetic Nanoparticles) in food systems and their possible repercussions on the food chain.

Vitali et al. [78] summarized in their review the results of 136 research articles and evidenced the presence of microplastics (MPs) in seafood, chicken, terrestrial snails, select fruits and vegetables, salt, honey, sugar, water, and a limited range of beverages, such as beer and wine. Research conducted by Liu et al. [79] indicated that early studies revealed the detrimental effects of MPs/NPs on the growth of various crops, in particular wheat. Furthermore, Wang et al. [74] found similar inhibitory effects on corn, while Bosker et al. [80] demonstrated the negative impact on cress and tomatoes. Additionally, Dong et al. [65] reported that seedlings of rice were highly susceptible to the toxic nature

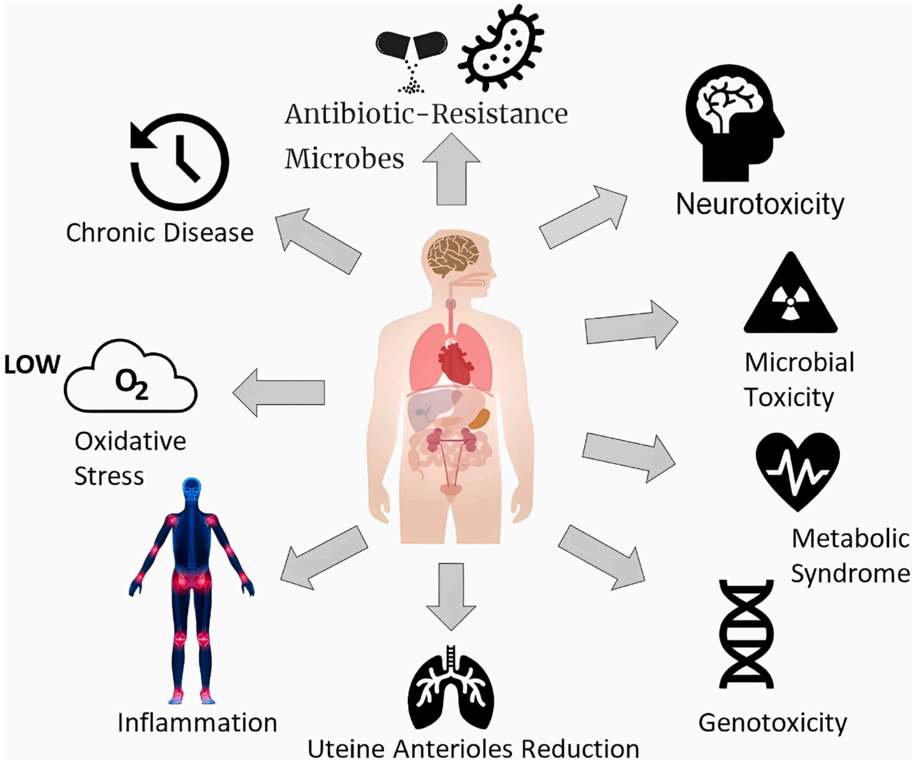

Fig. 5. Ingested plastics give rise to a multitude of issues within the human body, spanning antibiotic resistance, neurological complications, microbial toxicity, metabolic syndrome, gene toxicity, reduction in uterine arterioles, inflammation, oxidative stress, and chronic diseases.

of MPs/NPs. The extent of their toxicity was influenced by various factors. For instance, research conducted by Ma et al. [81] showed that the type of microplastics played a crucial role and polyvinyl chloride-based MPs (PVC-MPs) have been found to exert a more pronounced and destructive impact on metabolism, ionic homeostasis, and growth of crop plants, in comparison to polystyrene-based MPs (PS-MPs). In a latter study, conducted by Lian et al. [53,59], the exposure of lettuce plants to polystyrene nanoparticles (PS-NPs) resulted in a notable decrease in both plant biomass and nutritional quality. Specifically, the levels of leucine (30.1%), isoleucine (20.7%), valine (10.7%), lysine (22.2%), threonine (8.7%), and tryptophan, exhibited notable reduction in lettuce plants subjected to PS-NPs compared to the control group (36.9%). Additionally, the levels of semi- and nonessential amino acids, such as serine, proline, tyrosine, arginine, aspartate, ornithine, and asparagine, were also found to be lower in the PS-NP-treated plants than in the control groups.

Recent research on microplastics and nanoplastics exposure and toxicity revealed that the primary route of human plastic particle consumption is through ingestion. It is more likely that these particles enter the body via lymphatic tissue, and there is a particular possibility of their entry through phagocytosis or endocytosis, infiltrating the microfold (M) cells located in the Peyer's patches. Within the gastrointestinal (GI) tract, nanoparticles have the potential to interact with various molecules, including proteins, lipids, carbohydrates, nucleic acids, ions, and water [82]. Consequently, these nanoparticles become encapsulated by a collection of proteins referred to as a 'corona' [83]. Depending on the specific conditions they encounter, polystyrene nanoparticles can form different types of complex coronas. In a ground-breaking study by Leslie et al. [84], plastic particles were detected and quantified in human blood for the first time. The study identified polymers such as PS, PP, and PET in the blood samples. Moreover, two separate studies, conducted by Ragusa et al. [85] and Wick et al. [86], demonstrated that PS beads of various sizes (50, 80, and 240 nm) and microsized PP were able to permeate the human placenta. In another investigation, Nadanaciva et al. [87] found that PS-NPs (44 nm) internalized into human cells resulted in inhibited cell viability, altered gene expression, morphological abnormalities, and inflammation. Furthermore, during an in vitro study Hu & Palić [88], showed that PS particles with diameters of 202 and 535 nm induced inflammation in human lung cells. Additionally, Ye et al. [89] applying nanoparticles (21 nm and 48 nm in size) to myocardial cells, evidenced that the presence of MPs/NPs in the bloodstream and cardiac cells could potentially lead to blockage and disruption of normal circulation, thereby contributing to heart disease in humans. Moreover, the accumulation of MPs/NPs in the gut and liver demonstrated to trigger inflammatory responses, amplify lipid accumulation in the liver, and raise levels of catalase and superoxide dismutase enzymes, suggestive of oxidative stress, as demonstrated in a study by Lu et al. [90]. Meng et al. [12] showed that the exposure to PS-NPs and PS-MPs led to weight loss in mice, an increased mortality rate, significant alterations in multiple biomarkers, and histological damage to the kidneys. Their investigation also revealed that the presence of PS-NPs and PS-MPs triggered oxidative stress and the onset of inflammation (Fig. 5). Goodman et al. [91] showed the detrimental impacts of PS-MPs on human kidney and liver cells and evidenced that the ingestion of microplastics could give rise to toxicological issues affecting cellular metabolism and cell-to-cell interactions. Their results highlighted that the exposure of human kidney and liver cells to microplastics leaded to notable alterations in morphology, metabolism, proliferation, and induced cellular stress.

The dangers inherent in MP/NP are, also, linked to their ability to carry dangerous chemical substances, including those intentionally added in the production phase such as phthalates and Bisphenol A, and to environmental contaminants such as styrene, heavy metals, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs) that can be absorbed on their surface during their use and maintained in the environment. These chemicals are classified as endocrine disruptors and/or immunological disruptors. The evidence that NPs are able to overcome the intestinal barrier, to the point of penetrating the cells, support the hypothesis of interference of these substances with the metabolism, triggering a chronic state of inflammation, serious problems in development, infertility, warning some types of cancer, abnormal immune reactions which, over time, could lead to autoimmune diseases and cancer.

Food and Agriculture Organization of the United Nations (FAO) report "*Microplastics in Food Commodities. A Food Safety Review on Human Exposure through Dietary Sources*" [92] estimated the dietary exposure of consumers to MPs, and highlighted some knowledge gaps regarding their public health relevance offering some recommendations for future work on microplastics in support of food safety governance. The report outlined the currently available knowledge on the presence of microplastics in food products, which raised from various sources of contamination. The main recommendation therefore concerns the development, fine-tuning and harmonization of analytical techniques for (micro)plastics in food and for the assessment of acute and chronic exposures to components of micro/nanoplastics in various foods. Given the exponential growth of the impact of microplastics on the environment, there exists a pressing imperative to proactively diminish the origin of plastic pollution and formulate effective strategies to curtail the potential hazards linked to microplastics within our surroundings, ultimately safeguarding our well-being.

5. Conclusions

In light of ongoing societal advancements, embracing the reality of a plastics-centric era becomes inevitable. Presently, a multitude of untreated plastic waste infiltrates both the environment and soils through diverse pathways, subsequently undergoing fragmentation into minute plastic particles propelled by physical, chemical, and microbial mechanisms.

On terrestrial surfaces, substantial plastic refuse undergoes a transformation into smaller fragments due to factors such as animal ingestion and excretion, erosive forces from wind and rain, and the influence of ultraviolet radiation. In deeper soil layers, plastic waste degradation is facilitated by biological ingestion and digestion, with its destiny contingent upon factors like biological activity, hydrological patterns, as well as soil's physical, chemical attributes, and weathering processes.

Extensive research has revealed that microplastics have the capacity to accumulate within soil, thereby posing a significant threat to the broader ecosystem. The presence of microplastics in soil has the potential to impede nutrient uptake, hinder root growth, and compromise overall plant vitality. This, in turn, can result in diminished crop yields, potentially undermining food security. Moreover, the uptake of microplastics by plants has emerged as an escalating apprehension. Research demonstrates that plant roots can absorb microplastics, subsequently transporting them to various plant tissues, including those fit for consumption. This raises concerns about potential health hazards for humans who consume these contaminated plants. The microplastics may introduce harmful chemicals or serve as carriers for other pollutants, amplifying the potential risks. The ramifications of microplastics on human health are an ongoing area of investigation. Preliminary findings suggest that microplastics could elicit adverse effects on human health, manifesting as inflammatory responses, oxidative stress, and disruptions in normal cellular processes. Nonetheless, a more comprehensive understanding of the extent of these health risks and their long-term implications requires further in-depth exploration.

In summary, the existence of microplastics in soil poses a multifaceted threat encompassing the environment, plant life, food security, and potentially human well-being. It is imperative that additional research is conducted and awareness is heightened to develop effective strategies aimed at mitigating microplastic pollution and minimizing its deleterious impacts on soil quality, plant health, and human wellness.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The work described has not been published previously it is not under consideration for publicationelsewhere, its publication is approved by all authors and tacitly or explicitly by the responsibleauthorities where the work was carried out, and, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

Data availability

Data will be made available on request.

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