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MICROPLASTIC CONTAMINATION IN HYDROPONIC AGRICULTURE: SOURCES, TRANSPORT PATHWAYS, PLANT UPTAKE AND FOOD SAFETY IMPLICATIONS

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ABSTRACT

Microplastic contamination has emerged as an environmental concern in modern agricultural production, including hydroponic systems that are increasingly adopted for their efficient use of water, nutrients, and growing space. This review examines the sources, transport pathways, plant uptake mechanisms, and potential food safety implications of microplastics and nanoplastics in hydroponic agriculture. A structured narrative review of relevant scientific literature was conducted to evaluate the occurrence and behaviour of plastic particles in hydroponic environments, with particular attention to nutrient solutions, growing materials, agricultural infrastructure, and edible crops. The review identifies contaminated source water, degradation of plastic pipes and reservoirs, growing substrates, atmospheric deposition, and maintenance activities as potential pathways through which microplastics enter hydroponic systems. Once introduced, their movement and accumulation are influenced by particle size, polymer composition, surface characteristics, nutrient solution chemistry, and system design. Experimental evidence indicates that certain small plastic particles can penetrate plant roots and, under specific conditions, translocate into aboveground tissues, including edible portions of crops such as lettuce. However, the extent of particle uptake under commercial hydroponic conditions and the associated risks to human health remain insufficiently understood. The review also highlights limitations in existing analytical methods, particularly the difficulty of distinguishing external particle adhesion from internal uptake and the lack of standardized detection procedures. To minimize contamination, the study recommends improved source-water treatment, appropriate material selection, routine system maintenance, effective filtration, and reliable monitoring techniques. Further research involving environmentally realistic exposure conditions, different crop species, and standardized analytical methods is necessary to establish the implications of microplastic contamination for food safety. Overall, the review emphasizes the importance of evidence-based contamination prevention and sustainable management practices in ensuring the long-term safety and environmental sustainability of hydroponic agriculture.

Keywords: Microplastics; Nanoplastics; Hydroponic Agriculture; Plant Uptake; Transport Pathways; Food Safety; Nutrient Solutions; Plastic Contamination; Environmental Sustainability; Risk Assessment.

1 INTRODUCTION

Plastic materials are now used in modern food production due to their cheapness, durability, easy moulding and light weight. Their use in agriculture is in irrigation pipes, reservoirs, films, seedling trays, packaging, greenhouse covers, netting, and filters. These microplastics (MPs) are plastic particles less than 5 mm in size, and nanoplastics (NPs) are a smaller particle size that are less than 1/250th the size of an MP, with definitions varying on the upper size limit. The first attention to plastic pollution has come to light because of litter in the sea (Thompson et al., 2004). More comprehensive assessments of plastic manufacturing and distribution reveal the presence of significant amounts of plastic in the environment, and the fact that much of the plastic, especially smaller pieces, will stay in circulation for extended periods of time (Geyer et al., 2017). This waste comes from many land sources, and as such, land-use operations, such as agriculture, are directly linked to the broader issue (Jambeck et al. 2015).

Fresh and wastewater, soils, sediments and atmospheric deposition are now reported as sources of particles. These environmental compartments can contribute to food production systems in several ways through the introduction of plastic particles. The use of a nutrient solution either directly or with an inert or low-organic substrate for growing plants is often touted as an efficient alternative to field soil cultivation, which is generally called hydroponics. The controlled environment conditions may lead to better water use efficiency, nutrient delivery and consistency of crops. But a hydroponic system is by no means free of pollution from the environment. Particles can be transported in the water, fragments can be released by the polymer components and dust can be deposited by the air. Therefore, the environmental benefits of hydroponics have to be evaluated in conjunction with material flows needed for the hydroponic system.

Particularly, leafy vegetables like lettuce, spinach and herbs have a food-safety question, as they are easy to contaminate with germs. Their edible parts are in contact with the production area and are sometimes consumed with minimal processing. There should be a clear separation between particles being retained on the surface of the leaves, particles being retained on the roots, and the internalisation and transport of particles to edible shoots. The presence of particles on a crop does not necessarily imply internal uptake, bioavailability and/or a human-health effect. In this article, therefore, the evidence is critically examined and extrapolating observations made in the laboratory to estimates of consumer risk is avoided.

The goals are to determine the sources of MPs and NPs in hydroponic production, describe the transport and the incorporation of MPs and NPs, review the available evidence regarding uptake into roots and translocation, discuss analytical and food-safety issues, and suggest ways to prevent and monitor. Special emphasis is given to the evidence obtained from hydroponic cultures, and where there is no direct evidence from hydroponic culture, a limited use of evidence obtained from soil-grown and wastewater-irrigated plants is used to explain mechanisms.

2 METHODOLOGY

A structured narrative review approach is used for the current article. Literature was sought by conducting subject-specific searches on scholarly indexing and publishers' websites. The search concepts were: micro/nanoplastics in combination with hydroponics or soilless cultivation, nutrient solution or irrigation water, crop uptake, root translocation, lettuce, food safety and analytical detection. Fundamental research on the interactions between plants and plastic pollution, along with recent reviews and experimental studies, was presented. The selection of peer-reviewed journal articles reporting particle exposure, polymer identity, size, plant species, exposure matrix, uptake or environmental fate was prioritized. The field was mapped using a review and the primary studies were found through a review; where possible, quantitative claims were tracked to original research.

There are clear limitations with the review. Not a registered systematic review and does not purport to have included all publications. The number of direct hydroponic studies has been significantly less than soil-grown studies and the methods and exposure conditions vary widely. Therefore, a thematic synthesis of findings was conducted instead of statistically pooling findings. The methodological quality is a major focus issue itself. Koelmans et al. (2019) suggested that the quality of data varies greatly for freshwater and drinking-water research and that this can impact comparisons of studies. Similarly, Primpke et al. (2020) stressed the need to critically evaluate the analytical procedures before results can be harmonised. Thus, guidance on sampling and quality assurance/quality control is necessary as explained by Brander et al. (2020) for aquatic sampling and the same applies to hydroponic sampling. Therefore, this synthesis makes a clear separation between direct evidence and mechanistic inferences and highlights at what points conclusions are not yet definitive.

3 SOURCES OF MICROPLASTICS IN HYDROPONIC AGRICULTURE

Water is likely a likely first entry point. MPs can originate from urban runoff, wastewater discharges, and surface-water contamination, from fallout that is deposited from the atmosphere, or from degradation of the distribution system. A significant portion of the particles can be removed by the municipality, although this is usually not comprehensive. Advanced wastewater treatment technologies can effectively decrease the amount of particles in effluent but it has been demonstrated that their performance differs, according to Talvitie et al. (2017). Focal plane array (FPA) micro-FTIR imaging has also been used by Mintenig et al. (2017) to identify microplastics in treated wastewater effluent from wastewater treatment plants (WWTPs). Particulate matter that is not destroyed, is often transferred to sludge. Usually, there are particles in reclaimed wastewater that remain after treatment, unless there is advanced treatment or a special filter applied. Conditions of catchment, treatment processes, pipe materials and pipe storage will affect the concentration and size profile fed into a hydroponic unit.

Another potential source could be hydroponic infrastructure. Pipes, channels, tanks, connectors, net pots, rafts, clips and protective films are made of polyvinyl chloride (PVC), polyethylene, polypropylene, and polystyrene and others. Repeatedly touching flowing nutrient solution, washing, temperature fluctuations, exposure to ultraviolet light and mechanical maltreatment can cause surface embrittlement or abrasion. The fact that a plastic contains a plastic component doesn't mean that it is causing the release of a relevant particle load. Release rates vary with the polymer style, age, surface conditions and cleaning chemicals used and the velocity of the flow. However, infrastructure should not be assumed to be 'inert' and should be evaluated as a potential source.

The use of growing media and propagation materials may also be a source of particles. The fragments may come from the rockwool (a mineral fibre, not plastic), but also from plastic sleeves, plugs, foam substrates, polymer coated materials and seedling trays. Some commercial substrates are produced using polymeric foam and there are also mixed polymer residues that can be present in recycled materials. This is supported with evidence from soil systems. Bläsing and Amelung (2018) in their review of analytical methods and potential sources of plastics in soil, classified agricultural inputs as an important group. Additional potential sources are packaging, transport crates and disposable sampling equipment. A significant problem is the risk of cross-contamination during sampling as it can result in fibres or fragments being sampled from a synthetic origin and mistakenly identified as being part of the crop.

Deposition in air is important in greenhouses and indoor farms. Fibres can be shed from synthetic fabrics, food packaging, ventilation systems or external dust and fall on the open leaves and nutrient channels. The characteristics of microplastic and nanoplastic pollution in agroecosystems were summarized by Ng et al. (2018) and the various sources that can enter cropping systems via air, water and management practices were listed. Leafy vegetables are of large surface area and may contain particles in waxes, trichomes or irregularities of the surface. It can be a means of external contamination if the leaves are not washed and it is important when studies look at unwashed leaves or when surface contamination is not differentiated from tissue-bound contamination. Finally, particles can be redistributed in the manipulation of the process. Fragments may be released from channels as a result of high-pressure cleaning, channel scraping, wear of the cleaning pump or frequent changes of the cleaning tubing. Filters concentrate particles and allow other particles to be released back into the system through inadequate cleaning or backwashing. The best source control plan is therefore a full system audit which takes water, materials, air, inputs and maintenance into account.

Table 1: Potential sources and entry points of plastic particles in hydroponic production

Source	Possible mechanism	Relevant control
Source water	Particles transported from catchments, wastewater or distribution networks	Test input water; use appropriately selected filtration
Pipes, tanks and channels	Abrasion, ageing, UV degradation and mechanical wear	Specify durable materials; inspect and replace damaged components
Propagation and growing materials	Fragments from foam plugs, trays, sleeves and polymer substrates	Audit inputs; prefer traceable, low-shedding materials
Air and greenhouse dust	Deposition of synthetic fibres and fragments on leaves and reservoirs	Improve housekeeping; protect reservoirs; assess ventilation
Maintenance and packaging	Scraping, pump wear, packaging residues and sampling contamination	Use non-abrasive cleaning; control waste; apply blank controls

4 TRANSPORT PATHWAYS AND FATE WITHIN HYDROPONIC SYSTEMS

After being introduced, the MPs and NPs are transported through the system depending on the particle size, shape, density, surface charge, and on the sort of the polymer and the nutrient solution chemistry. The larger, denser particles might accumulate in reservoirs or low-flow areas, while the smaller particles and fibres can stay suspended in the flow and continue to circulate through the pump or channels. Nutrient solutions include dissolved salts, organic exudates and microorganisms which can affect the aggregation and surface properties of particles. Under certain conditions, particles can be made more prone to aggregation by the use of electrolytes, but particles can also be stabilised by organic coatings, or their surface affinity modified.

Soil environment evidence assists in elucidating the distribution of particles in a growing medium. What does not seem to have happened has been reported by Zhang and Liu (2018): They found that microplastics in the soil were not uniformly distributed in the various soil aggregate fractions, indicating that microplastic particles are not predominantly found in one place and are distributed across a range of physical compartments. The same can also be found in hydroponic substrates and in mat rooting systems where different particles may stay in the hydroponic system and get stuck in the roots more than others. Another way soil organisms can move particles is by adhering them to their bodies. Huerta Lwanga et al. (2016) studied microplastics in the terrestrial ecosystem in relation to the earthworm Lumbricus terrestris, and research shows microplastics can be ingested and transported by biota. While a hydroponic system may not have earthworms present, the underlying premise of the organisms and physical processes disturbing particles is applicable to any hydroponic system with biofilms or any invertebrates present.

Recirculating systems allow for multiple opportunities for particle–root contact. Different types of nutrient film systems have distinct hydraulic residence times, turbulence, sedimentation, and exposure of the roots to the nutrient film. Particles can be trapped by root mats, filtered, or attached to the biofilms. Roots and biofilms can also be a sink but can also be a source if later detached from the root or reef by flow or maintenance. Thus a single sample taken from the outlet of the reservoir could reflect an underestimate of the total particle load to various system compartments.

Risk and transport change withe ageinging of particles. A polymer surface may undergo changes due to weather by: ultraviolet radiation, oxidation, and heat and mechanical stress, which can cause fragments to fall out or form cracks. Older particles can be contaminated with additives, metals or hydrophobic organic contaminants that have been adsorbed to the surface. The broader challenges of the particles' impact on soil function have been raised by de Souza Machado et al. (2018b), who studied the impact of microplastics on the biophysical environment of the soil, that is, on physical conditions, which affect water and root behaviour. These changes indicate that changes can have an impact on the environment in which plants are growing, not just in physical proximity. Other sources of exposure due to vector effects are possible since plastics are likely to carry other contaminants, but should not be expected to be the only source in all hydroponic situations. It would have to be tested in the conditions of a realistic nutrient solution.

System design also affects transport and retention. Small emitters can get clogged because of fibres or aggregates, and in large reservoirs, settling takes place. Fine filtration will decrease particle loads, but may increase pressure loss and maintenance. The presence of microplastics in terrestrial ecosystems and soil was ignored almost at the beginning, as pointed out by Rillig (2012) who stressed that the agricultural soils may be a long-term reservoir. There are other systems that use hydroponics but the lesson is applicable: anything that captures the particles becomes an accumulation of particles that needs to be managed. The staged system (source water treatment, pre-filtration and periodic cleaning of reservoirs) is more feasible than using a single filter. Filters should be selected based on the measured particle size distributions, and should include the safe disposal of solids collected by the filter.

5 PLANT UPTAKE, RETENTION AND TRANSLOCATION

Exposure to plants can be via roots, shoots and possibly stomatal or cuticular interfaces. In controlled experiments it is the pathway of root exposure that has been studied the most. The fate of particles in the external and internal tissues is determined by the presence of root mucilage, pores in the cell walls, apoplastic barriers and the endodermis. The particle size is the most significant determinant, but the polymer composition, shape and surface charge and developmental stage of the roots are also important. A clear difference between adsorption to the root surface and actual internalisation is important as it is both these that can give positive analytical signals in whole root samples.

Li et al. (2020) presented compelling evidence that submicrometre and micrometre-sized polystyrene and polymethyl methacrylate particles were able to enter wheat and lettuce through a lateral-root emergence pathway (crack-entry pathway). Particles were found in the stele and could be transported from roots to shoots which was enhanced during transpiration. It shows it's possible with experiments, but not proven in humans. It does not mean, however, that all types of particles and all sizes of polymer can easily enter the commercial crops in operational farms. In extrapolating

these findings all the following must be taken into account: exposure concentration, particle preparation, use of model particles.

Uptake is not the only response of plants to particles. Rillig et al. (2019) stated that the impacts of microplastics on plants are unknown, but that an effect on plant communities and organisms in the soil might result in impacts further down the food chain. de Souza Machado et al. (2018a) suggested that microplastics are a new threat to terrestrial ecosystems and that impacts on plant communities and soil organisms might cascade through the food web. Boots et al. (2019) reviewed evidence that impacts of micro-plastics on soil ecosystems are both above and below-ground, and thus plants can be impacted both through root interactions and changes in the rest of the biological communities. Such observations suggest that the crop and the microorganism and faunal environment should be considered for exposure assessment.

The interaction of particles is different with various plant species and plant morphology. Lettuce and other leafy crops are especially significant as they are eaten as the shoot. There can be particles in tissues that are near the soil or solution interface for root crops; partitioning can be different for fruiting crops. Uptake may vary by root architecture, by the transpiration rate, by the stage of growth and by stress levels. Also it should be noted that a difference exists between particle uptake and dissolved additives or chemicals that leach out of the plastic; the presence of additives or chemicals in the dissolved state does not necessarily imply that particles were able to cross plant barriers.

Foliar exposure can be critical in enclosed production, and may be at least as important as root exposure. Airborne fibres can settle on leaves and very small particles can attach to the surface of leaves. The presence of a particle on a leaf should not, however, be taken to indicate systemic translocation. Rigorous washing and surface sterilisation (where necessary), microscopy of tissue sections and polymer-specific confirmation should be part of an experimental design. If no external deposition controls are in place, external deposition may appear as internal contamination and the deposited data could appear to give an exaggerated risk for the edible portion.

For hydroponic growing, direct root contact and the lack of soil buffering may allow for the possibility of some exposures to be more immediate. However, nutrient solution is different from soil in terms of the organic matter, mineral surfaces and microbial complexity. It should not be assumed, therefore, that a greater or lesser toxicity exists based on comparative evidence. Experimental work will need to be carefully done to decide if the balance between adsorption, internalisation and biological effects change for hydroponic culture.

Table 2: Key factors governing plant exposure and interpretation of uptake evidence

Factor	Likely influence	Evidence and interpretation issue
Particle size	Smaller particles may access root barriers more readily	Detection limits strongly affect reported size distributions
Polymer and surface chemistry	Affects density, charge, aggregation and sorption	Model polystyrene results cannot represent every polymer
Root development	Lateral-root emergence may create entry points	Internalisation must be separated from root-surface adhesion
Transpiration	May influence movement with water flow	Species and environmental conditions alter transpiration
Leaf deposition	Can contaminate edible surfaces directly	Washing and tissue localisation are essential

6 FOOD SAFETY AND ENVIRONMENTAL SUSTAINABILITY IMPLICATIONS

The hazard identification, exposure assessment and risk characterisation stages of food-safety assessment should be kept apart. Consumer exposure will be dependent on the concentration of the particle in the crop, the edible part of the crop, washing and processing, frequency of consumption and particle size and the percentage remaining after digestion. There is a lack of harmonisation of current analytical methods in order to allow for reliable comparisons between many crop studies. Evidence of human health effects is still under investigation. Lehner et al. (2019) investigated the environmental occurrence and the potential health impacts of nanoplastics, as the smallest particles could have different properties to larger pieces. Prata et al. (2020) examined the possible human health impacts of exposure to microplastics in the environment, highlighting that exposure to microplastics has a poorly-defined relationship to impact on human health. The dose–response relationship is therefore uncertain as is the fate of the particles in the gastrointestinal tract and the role played by the associated chemicals.

Humans are not only at risk of exposure but actual exposure has occurred. Plastic particle pollution was found and measured in human blood, showing that it can enter the systemic circulation (Leslie et al., 2022). The study does not point to a source of these particles, nor define a 'pathway' for exposure, and cannot alone demonstrate a causal link with food. However, it does suggest that the exposure route to humans should be considered for several routes. Likewise, Rochman et al. (2015) detected plastic debris and fibres from textiles in fish and bivalves for human consumption, which is the case in other food systems. The findings are applicable to hydroponic vegetables as they indicate that the food chain can move these particles; but they are not evidence that the food chain is contaminated to harmful levels in hydroponic vegetables.

Irritative interactions with biological barriers, inflammatory response, oxidative stress, and the presence of additives and sorbed pollutants are potential hazards. Most of the evidence for mechanism comes from cell, animal or high dose experimental systems, however. These observations cannot be scientifically translated to a definite clinical risk of hydroponic vegetables. Likewise, poor risk estimates do not demonstrate "no risk. A precautionary approach complements the development of more evidence to minimize unnecessary exposure.

Crop contamination is just one aspect of environmental sustainability. Hydroponic systems can also save water and land, but in order to achieve this they will require electricity, fertiliser production, plastics, packaging, nutrient discharge and end-of-life management. The Food and Agriculture Organization (FAO, 2021) emphasized the need to act on agricultural plastics and their sustainability noting that the use of plastics in agriculture is often poorly managed throughout its life cycle. If materials are replaced or disposed of often or poorly, plastic particle release can adversely affect sustainability. The service life and recyclability of pipes, channels or films, and the fate of filters and maintenance residues should therefore be taken into account as well as the fate of contaminated residues.

Another consideration is removal of particles from the gas stream to sludge or solid waste. When this material is used on the land or not managed properly, it can become contaminated and transport from a controlled farm to land and water sources. Circular-economy strategies should not be about moving plastic pollution. Material traceability, cleaning and contamination consideration is required for reusing and recycling. The goal of sustainability is to not release materials, to make equipment last as long as possible and to ensure that materials captured go into appropriate waste streams.

7 RECOMMENDATIONS AND RESEARCH PRIORITIES

The best place to start is source control for hydroponic operators. Specs may specify materials that is durable, u/v and chemical resistant and has been tested to be safe for food contact. Systems should minimize the use of unnecessary single-use plastics, and should not use abrasive cleaning materials, nor should replacement schedules be set for arbitrary reasons, but should be set in accordance with inspection. Supplier declaration of materials should be requested also information on additives, if available. These measures will not take away all the particle sources, but will help to minimise unnecessary shedding.

In surface water or reclaimed wastewater systems, the water inputs should be described prior to system adoption. Water quality standards for drinking water can be used as a benchmark for drinking water, but the World Health Organization (WHO, 2019) guidelines on microplastics in drinking water were developed for drinking water, not irrigation water. Monitoring should include samples of source water, reservoir solution, filters, root-zone residues and edible tissues in a risk-based monitoring plan. Sampling should adhere to the quality assurance principles described by Brander et al. (2020) including the inclusion of field blanks, procedural blanks and airborne controls. The identity of the polymer should be confirmed by the use of micro-FTIR or Raman spectroscopy or validated thermal methods, rather than only visual appearance or fluorescent staining, in the laboratory. Limit of size, particle shape, polymer type, mass recovery and particle number recovery should be reported.

The treatment trains should be based on measured particle sizes. Where suitable, coarse screening and sedimentation and granular or membrane filtration can be combined. Documentation relating to filters must be maintained for disposal of captured wastes. The operators need to be aware that not all the microplastic fractions can be removed by a turbidity or suspended solids rated filter. If the removal of settled solids and the cleaning of biofilms are undertaken regularly, they can limit the accumulation of solids in recirculating farms, without causing an increase in the fragmentation.

Limited exposure information and an uneven evidence base across exposure routes are drawn attention to in the WHO (2022) rapid systematic review on dietary and inhalation exposure to nano- and microplastic particles. This conclusion calls into question both sides of the declaration of proportionality in action, without offering definitive proof. Research priorities involve long-term trials with aged and environmentally realistic particles, with various types of polymers, low exposure concentrations, and commercially relevant crop varieties. Studies must be separated into external adherence and internal uptake of particles and amount of particles present in roots, stems and edible parts of the plants

individually. There is a need for analytical intercomparisons and reference materials in an emergency. Furthermore, scientists should investigate the interaction of microplastics with the availability of nutrients, beneficial microbes, pathogens and chemical contaminants in the rhizosphere.

Table 3: Practical risk-management framework for hydroponic operators

Priority	Action	Verification
Prevention	Material procurement standards and infrastructure inspection	Supplier declarations; maintenance records
Input control	Characterise water and propagation materials	Periodic source-water testing
Treatment	Use staged filtration and reservoir solids management	Filter performance and waste logs
Monitoring	Sample water, roots and edible tissues with blanks	Polymer-confirmed analytical reports
Governance	Adopt transparent reporting and safe waste disposal	Audits and documented corrective actions

It is important to consider both the crop and the system when assessing risk. Leafy vegetables should not be used as a substitute for root crops, or fruiting crops. Washing and food preparation should be a component of exposure assessments, and realistic particle size and concentration should be a focus of toxicological work. Regulators and industry bodies should create uniform guidance for monitoring that does not put unduly restrictive limits that are not backed by valid analytical support. Alarmist statements as well as blanket assurances will not do the job as well as transparent reporting of uncertainty will do it.

8 CONCLUSION

There is a potential threat to hydroponic agriculture from microplastic contamination, via water, air, infrastructure, substrates and activities. Particles are affected by the recirculation, root mats and filters. Experimental studies have demonstrated the ability of very small particles to penetrate into the roots and in some instances into upper plant parts. However, the uptake level in commercial hydroponic production and associated dietary exposure are still poorly characterised.

The hydroponic system therefore must be considered a production area which can be controlled and which is not necessarily particle-free. Proportionate actions include source control, appropriate materials, water treatment, monitoring and strong analytical quality assurance. Future studies need to go beyond the use of "pristine" particles and short-term high dose experiments, to nearer-to-realistic exposure scenarios and food-chain risk assessment. Taking precautions based on evidence and avoiding reaching conclusions without evidence can help maintain environmental sustainability without reaching conclusions on safety for hydroponically grown vegetables.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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