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Citation

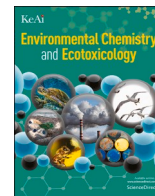
Qin, P., Dijkstra, J. M., Duijndam, A. J. A., Jabbour, C. R., Mandemaker, L. D. B., Meirer, F., ... Bosker, T. (2026). Comparative uptake and translocation of polyvinyl chloride (PVC) and polypropylene (PP) nanoplastics in carrot, lettuce, and wheat. *Environmental Chemistry And Ecotoxicology*, 8, 2344-2356. doi:10.1016/j.enceco.2026.06.007

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Note: To cite this publication please use the final published version (if applicable).



Research Paper

Comparative uptake and translocation of polyvinyl chloride (PVC) and polypropylene (PP) nanoplastics in carrot, lettuce, and wheat

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ARTICLE INFO

Keywords:

Nanoplastics

Edible plants

Uptake

Translocation

Biodistribution

ABSTRACT

Plastic particles smaller than one micrometer, termed nanoplastics (NPs), are pervasive in agricultural systems. Uptake of these particles in plants has been demonstrated, yet cross-species comparisons remain scarce, with most work to date focusing on polystyrene particles. Here, we investigated how gadolinium-labelled polyvinyl chloride (PVC; ~257 nm) and polypropylene (PP; ~352 nm) NPs are taken up and redistributed in three representative crops, carrot (*Daucus carota*), lettuce (*Lactuca sativa*), and wheat (*Triticum aestivum*). Using inductively coupled plasma–mass spectrometry, we quantified the Gd label to calculate the NP accumulation in roots and shoots. All species absorbed both types of NPs, with roots consistently serving as the dominant reservoir and root concentrations exceeding shoot concentrations by one or two orders of magnitude. Root-to-shoot translocation was generally limited, with translocation factors typically below 5%, but varied strongly among species, ranging from <1% in wheat to approximately 4% in carrot, with lettuce showing intermediate values. Differences between PVC and PP were also observed, with PVC showing higher uptake and translocation compared to PP. We also observed species-dependent growth responses, with lettuce exhibiting a reallocation of biomass from roots to shoots, whereas carrot and wheat were largely unaffected. These results highlight the need to consider both crop-specific traits and polymer type when assessing NP uptake and redistribution in plants, while the potential implications for food safety and health risks in agroecosystems should be evaluated further under soil-based and environmentally realistic exposure conditions.

1. Introduction

Plastic pollution has become a major environmental issue due to the widespread use and persistence of plastics. Global production is currently over 400 million tons, and expected to further increase [1]. Substantial amounts of plastic waste have already escaped into the environment, and are persisting within various ecosystems [2–4]. Terrestrial environments, particularly agricultural soils, are increasingly recognized as long-term sinks for micro- and nanoplastics (MNPs), mainly due to multiple agricultural inputs [5–7]. Sources include plastic mulch films, biosolid applications, sewage irrigation, and polymer-based agrochemicals, as reviewed by Ren et al. [8]. Reported

concentrations range from hundreds of particles per kilogram in crop-lands to over 10,000 mg·m⁻³ in intensively mulched soils [9–11], with polyethylene, polypropylene, polystyrene, and polyvinyl chloride among the most commonly detected polymers [12,13].

Growing evidence, summarized in Wang et al. [7], showed that MNPs can modify the soil structure, fertility, and contaminant availability, with potential downstream effects on crop yields and greenhouse gas emissions. In parallel, MNPs can disturb soil bacterial communities, reduce diversity, and shift functions linked to carbon decomposition and nitrogen cycling, especially under prolonged exposure [14–16]. At the plant level, MNPs can accumulate in tissues and induce oxidative stress, metabolic disruption, and growth inhibition; the responses vary with

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<https://doi.org/10.1016/j.enceco.2026.06.007>

Received 29 April 2026; Received in revised form 16 June 2026; Accepted 21 June 2026

Available online 22 June 2026

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polymer type, particle size, and species [17,18]. Foundational studies reported species-dependent growth inhibition under PS-MNP exposure [19] and demonstrated that MNPs can trigger reactive oxygen species and antioxidant defenses [20,21]. Further studies confirmed adverse effects on germination, root elongation, and antioxidant enzyme activity [22], while a meta-analysis highlighted consistent reductions in biomass and chlorophyll content [23]. Nanoplastics (NPs, particles <1 µm) are of particular concern because their small size and large surface area favor close interaction with roots [17,18].

NPs can be taken up by plant roots and subsequently translocated to other tissues after internalization [24–26]. Once inside plant tissues, NPs may interfere with physiological processes, leading to reduced biomass, chlorophyll content, and root elongation, as well as enhanced antioxidant activity [17]. In wheat and lettuce, sub-micrometer plastic particles can enter at lateral-root junctions and move upwards with the transpiration stream [27]. Multiple tracer-based studies further indicate that PS-NPs accumulate predominantly in roots with limited transfer to shoots: in lettuce, europium-labelled PS showed substantial root accumulation but <3% shoot translocation under high exposure [24]. Lettuce exposed hydroponically to Eu-labelled PS displayed strong root enrichment with minimal shoot transfer [26]; and mass-based measurements detected PS-NPs in both organs, yet at much lower levels in aerial tissues [25]. Most work has focused on PS, leaving other common agriculturally relevant polymers (e.g., PP, PVC) understudied, and most commonly, only one or two species were tested at the same time. Species traits likely mediate uptake; for instance, fibrous monocot root systems may present different entry opportunities than dicot roots with larger lateral gaps [17], while direct, cross-species comparisons under harmonized conditions remain scarce.

Here, we advance current understanding by comparing NP uptake and translocation in carrot (*Daucus carota*), lettuce (*Lactuca sativa*), and wheat (*Triticum aestivum*) exposed hydroponically to gadolinium-doped PP and PVC NPs at 50, 500, and 5000 µg·L⁻¹. Gadolinium labelling enables sensitive quantification of NP distribution in roots and shoots via ICP-MS [24]. Exposure concentrations were selected to ensure reliable tracer quantification rather than to replicate field conditions; however, by applying identical conditions across three crops and two polymers, this study moves beyond single-species or single-polymer assessments to provide controlled, comparative insights into NP uptake and redistribution processes across ecologically and agriculturally relevant crop types, and their implications for crop health.

2. Materials and methods

2.1. Nanoplastics

2.1.1. Particle preparation, characterization, and baseline determination

Spherical polyvinyl chloride (PVC) and polypropylene (PP) NPs (1% and 0.4% w/v, respectively) doped with Gd were obtained from CD Bioparticles (Shirley, NY, USA) and stored at 4 °C until use. Supplier-reported median diameters were ~ 257 nm (PVC-Gd) and ~ 352 nm (PP-Gd). Hydrodynamic particle size and zeta potential were further characterized using multi-angle dynamic light scattering (MADLS). PVC NPs had a mean diameter of 274.3 ± 20.4 nm and a zeta potential of -8.65 ± 0.37 mV, whereas PP NPs showed a larger mean diameter of 439.2 ± 50.3 nm and a zeta potential of -11.72 ± 0.49 mV (mean ± SD). PVC and PP were selected as representative high-production-volume polymers frequently detected in agricultural environments. The particles used in this study were commercially produced, pristine primary NPs, and no artificial ageing procedures were applied prior to exposure. Particles were selected based on the availability of tracer-labelled materials. The Gd label was embedded within the polymer matrix of the NPs and is therefore not expected to alter surface chemistry. Prior to dosing, working suspensions were gently vortexed (60 s) to ensure homogeneity. The particles were characterized from the suspension using attenuated total reflection infrared spectroscopy (ATR-IR

– PerkinElmer Frontier; MCT detector; 4 cm⁻¹ resolution) and scanning electron microscopy (SEM – Helios Nanolab G3, Thermo Fisher Scientific; beam current 50 pA, acceleration voltage 2 kV) to confirm their physico-chemical properties. For ATR-IR, multiple droplets (~ 80 µL) of NP suspension were drop casted onto a gold-coated Si wafer. The wafer was pressed on the ATR-IR crystal with material facing the crystal. For SEM, 10 µL of NP suspension was drop casted onto a Si wafer. Subsequently, the wafer was stuck onto an SEM stub, and the sample was coated with 6 nm of Pt to ensure conductivity by a sputter coater (Cressington 208HR) equipped with a thickness controller (Cressington MTM20). As seen in Fig. S1, ATR-IR reveals the expected PVC and PP vibrational bands for the reference materials. Additionally, for PVC, there are bands representing -OH and C=O stretches, which are likely coming from the Tween 20 and polyvinyl alcohol (PVA) surfactants. For PP, there are similar additional bands visible, and the broader potential C-O vibrations in the fingerprint area, which also point towards these surfactants and perhaps remaining isopropanol. As the concentration of surfactant is less than 1% of the media, it is relatively similar to the 1% polymer mass, explaining their presence here. This is confirmed by SEM, where the dried droplets of solution show no clearly defined particles at these concentrations but instead a dense drying spot of surfactant and NPs together (Fig. S2). However, as these standards will be diluted by a factor 2000–200,000 (PVC) or 800–80,000 (PP), the surfactants are expected not to adversely affect plant performance [28]. To establish reference Gd contents for subsequent mass-balance calculations, aliquots (1 mL) of each stock suspension were completely digested (H₂SO₄: HNO₃ = 1:8, v/v; 70 °C, 48 h) and analyzed by ICP-MS (NexION 2000, PerkinElmer, Shelton, CT, USA). The resulting total Gd values were 0.35% w/w for PVC-Gd and 0.30% w/w for PP-Gd. These data served as particle-specific reference concentrations in all uptake and translocation calculations.

2.1.2. Tracer stability

To verify that the metal label remained particle-bound under exposure conditions, dialysis tests were performed in (i) standard Hoagland nutrient solution (the hydroponic exposure medium; pH 6.0 ± 0.2) and (ii) a plant-environment solution formulated to mimic ionic conditions within xylem sap [26]. Pre-hydrated Pur-A-Lyzer™ tubes (Sigma-Aldrich, Burlington, MA, USA) were loaded with 125 µL of PVC-Gd or PP-Gd stock (5000 mg·L⁻¹) and immersed in 24.9 mL of the corresponding medium (*n* = 3 per polymer × medium). External aliquots (1 mL) were collected at 0, 24, 72, and 168 h, covering the maximum residence time of NPs in the exposure medium between renewals, digested (H₂SO₄:HNO₃ = 1:8, v/v), and analyzed by ICP-MS. Across media and time points, cumulative Gd release remained <2% of the particle-bound pool with no time-dependent increase (*p* > 0.05), confirming stable association of Gd with both NPs during plant exposure.

2.2. Plant experiment

2.2.1. Species and pre-culture

Seeds of carrot (*Daucus carota*), lettuce (*Lactuca sativa*), and wheat (*Triticum aestivum*) were purchased from Cruydt-Hoeck B.V. (Nijberkoop, the Netherlands). These species were selected to represent different crop types and edible plant organs, including a root vegetable (carrot), a leafy vegetable (lettuce), and a cereal crop (wheat), thereby enabling comparison of NP uptake and translocation across contrasting plant functional groups relevant to human consumption. The seeds were surface-sterilized in 0.5% NaClO for 30 min, rinsed thoroughly with deionized water, and germinated on moist filter paper wetted with Hoagland solution. For each species, visually uniform seedlings at an early seedling stage were selected to reduce within-species variation in initial plant size and developmental status. Uniform seedlings were transferred to glass test tubes containing Hoagland solution and pre-grown hydroponically for 7 days in a controlled climate chamber (20 ± 1 °C, 16:8 h light/dark cycle, 70% relative humidity). After this pre-

culture period, all plants were still in the seedling/early vegetative stage, and NP exposure was initiated at this stage for all species. To minimize contamination, all media preparation and transfers were performed with bleach-washed labware.

2.2.2. Nanoplastic exposure setup

Plants were exposed hydroponically to three nominal concentrations of each type of NPs (50, 500, and 5000 $\mu\text{g}\cdot\text{L}^{-1}$) in Hoagland solution. An unexposed control served as baseline. Reported plastic particle concentrations in agricultural soils are highly variable and commonly expressed as particle numbers, mass per dry soil, or percentage by soil mass, making direct conversion to hydroponic $\mu\text{g}\cdot\text{L}^{-1}$ exposure concentrations not feasible [29]. In soil systems, MNP bioavailability is further controlled by sorption to soil particles, aggregation, organic matter interactions, pore-water partitioning, and microbial processes [30,31]. Soil-based plant exposure studies using tracer-labelled model MNPs have applied elevated concentrations, such as 400 and 4000 $\text{mg}\cdot\text{kg}^{-1}$ dry soil, to enable quantitative assessment of plant uptake [32]. Therefore, the hydroponic concentrations used here should not be interpreted as field-equivalent soil concentrations. They were chosen for two reasons. First, pilot calculations showed that, at lower exposure levels, the resulting Gd signal would fall below the reliable detection limits of ICP-MS once the NPs were distributed within plant tissues. Second, the concentration range is consistent with previous tracer-labelled NP exposure studies in plant-based systems (e.g., see [24,26,33]). Thus, the primary objective was not to reproduce a specific environmental exposure scenario, but to enable robust, cross-species comparisons of polymer-specific uptake and translocation under controlled conditions. Consequently, the findings should be interpreted as mechanistic and comparative evidence of plant NP uptake and internal redistribution, rather than as a direct quantitative prediction of environmental risk under field-relevant agricultural soil conditions. Each species $\times$ treatment combination was replicated eight times (7 treatments $\times$ 3 species $\times$ 8 replicates = 168 experimental units). Test media were renewed every three days to maintain nutrient availability and to limit prolonged particle residence in the hydroponic medium, where aggregation or sedimentation may occur. This renewal regime ensured that the residence time of NPs in the exposure medium did not exceed 7 days, matching the time frame over which tracer stability was independently verified. Specifically, the renewal alternated between (i) replenishing the volume lost during plant growth with fresh Hoagland solution and (ii) completely replacing the medium with freshly prepared Hoagland solution spiked with NPs at the designated concentrations. To evaluate particle stability under exposure-relevant conditions, additional MADLS measurements were performed after 7 days of incubation in Hoagland solution. Compared with the initial characterization, the hydrodynamic diameter increased from 274.3 ± 20.4 nm to 483.0 ± 19.7 nm for PVC and from 439.2 ± 50.3 nm to 935.3 ± 51.8 nm for PP. In contrast, zeta potentials changed only slightly, from -8.65 ± 0.37 mV to -7.10 ± 0.65 mV for PVC and from -11.72 ± 0.49 mV to -11.09 ± 0.45 mV for PP. These results indicate aggregation in Hoagland solution, particularly for PP, while surface charge remained broadly stable. This is consistent with previous observations that increased ionic strength in aqueous media can shield electrostatic repulsion between plastic particles and promote agglomeration [34]. After 14 days of exposure, plants were gently but thoroughly rinsed with deionized water prior to tissue processing to minimize contributions from externally adhered particles, following procedures commonly applied in nanoplastic uptake studies [24,26]. Specifically, roots were rinsed three times with deionized water for approximately 30 s each under gentle manual handling. No ultrasound or mechanical agitation was applied, in order to avoid damage to the root surface and preserve tissue integrity. This procedure was intended to reduce loosely attached external particles while avoiding tissue disruption, although complete removal of strongly bound particles from root mucilage or surface structures cannot be guaranteed. This standardized rinsing procedure was applied uniformly across all

treatments and species. Plants were then blotted dry and processed for growth measurements and chemical analysis.

2.3. Growth and uptake assessments

2.3.1. Plant harvesting and growth measurements

Immediately after harvest, root length, shoot length, and fresh biomass of roots and shoots were recorded using a ruler and digital balance (± 0.01 mg) [35]. Tissues were then oven-dried at 70°C for 24 h to determine dry biomass, following established protocols [36].

2.3.2. ICP-MS quantification of Gd

Dried plant tissues (roots; shoots including stems and leaves) were weighed and digested in 1 mL of concentrated acid ($\text{H}_2\text{SO}_4\text{:HNO}_3$, 1:8 v/v) in acid-resistant tubes (Corning® 15 mL centrifuge tubes) at 70°C for 48 h. For each replicate, the entire dried plant tissue (root or shoot fraction) was digested as a single sample without subsampling. Complete digestion was confirmed by visual inspection, as digests were clear and free of visible particulates prior to dilution. After cooling, digests were brought to 10 mL with Milli-Q water and subsequently diluted 10-fold to meet instrumental acid requirements. Gd concentrations were quantified by ICP-MS operated under standard conditions for trace metal analysis. Prior to analysis, all samples were fully digested in concentrated acid, ensuring that Gd was present in dissolved ionic form. Therefore, calibration using aqueous, matrix-matched standards was considered appropriate, and no difference in analytical response between particle-associated and dissolved Gd was expected after digestion. External calibration was performed using matrix-matched standards covering the concentration range of the samples, with linearity consistently exceeding $R^2 = 0.999$. Instrumental drift was monitored using independent check standards (quality control solutions with known Gd concentrations) analyzed periodically throughout the measurement sequence. Procedural blanks and duplicate samples were included in each analytical batch to monitor potential contamination and analytical reproducibility, following general ICP-MS quality-control considerations described in previous trace-element studies [37]. Blank signals were negligible relative to sample concentrations, indicating no evidence of substantial cross-contamination during digestion or measurement, and duplicate measurements showed good reproducibility. Although dedicated matrix-spike recovery and LOQ values were not available for the original analytical batch, the combination of matrix-matched calibration, independent check standards, procedural blanks, duplicate measurements, and blank correction was used to ensure the reliability of the Gd quantification. All data were blank-corrected prior to calculation of uptake and translocation metrics.

2.3.3. Uptake and translocation calculations

NP uptake was expressed in two complementary ways: (i) as the concentration of particles in plant tissues ($\text{mg}\cdot\text{kg}^{-1}$ dry weight), and (ii) as the total mass of accumulated particles per tissue (root or shoot). These metrics reflect, respectively, the relative enrichment of particles within tissues and the absolute amount of particles accumulated.

To evaluate internal transport of NPs within the plant, the translocation factor (TF) was calculated as the ratio of the NP concentration in shoots (including stems and leaves) to that in roots:

$$\text{Translocation Factor} = \frac{\text{NP concentration in Shoots}}{\text{NP concentration in Roots}}$$

For ease of interpretation, TF values are presented as percentages (TF $\times$ 100%) in figures and tables unless otherwise stated.

Together, these metrics provide quantitative information on NP uptake and the relative extent of root-to-shoot translocation across crop species, polymer types, and exposure levels.

2.4. Statistical analysis

Statistical analyses were conducted in IBM SPSS Statistics v27.0. For each response variable, data from eight biological replicates (mean $\pm$

SE) were first screened for normality using the Shapiro–Wilk test and for homogeneity of variance with Levene's test. When these assumptions were satisfied, a two-way analysis of variance (ANOVA) was applied using polymer type (PVC, PP) and concentration (0, 50, 500, 5000

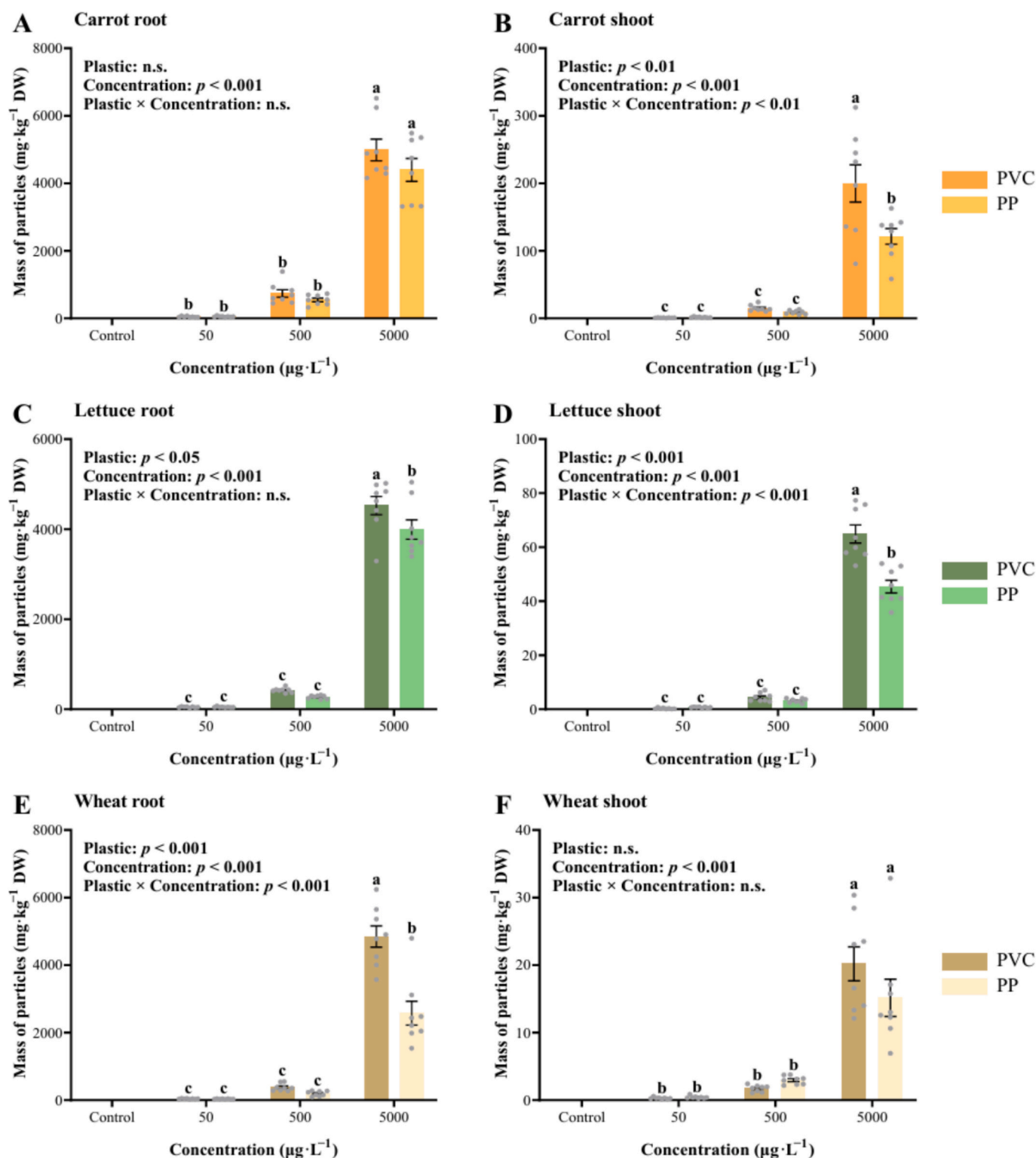


Fig. 1. Mass of particles (mean $\pm$ SE, expressed as $\text{mg}\cdot\text{kg}^{-1}$ dry weight, DW) in roots and shoots of carrot (*Daucus carota*, A–B), lettuce (*Lactuca sativa*, C–D), and wheat (*Triticum aestivum*, E–F) after 14 days of hydroponic exposure to three concentrations (50, 500, and 5000 $\mu\text{g}\cdot\text{L}^{-1}$) of PVC-Gd and PP-Gd NPs. Two-way ANOVA results for the effects of plastic type, concentration, and their interaction are shown within each panel. Different letters above bars indicate significant differences between treatments within each species (one-way ANOVA followed by Tukey's post-hoc test, $p < 0.05$); n.s. indicates no statistically significant difference. Error bars represent standard errors.

$\mu\text{g}\cdot\text{L}^{-1}$) as fixed factors. A significant polymer $\times$ concentration interaction ($p < 0.05$) prompted simple-effects analyses followed by Tukey's honestly significant difference (HSD) comparisons. If the interaction term was non-significant, data were pooled across polymers and analyzed with a one-way ANOVA; Welch's ANOVA was substituted when variances were unequal. In cases where both normality and homoscedasticity were violated, a Kruskal–Wallis test with Dunn's post-hoc comparisons (Benjamini–Hochberg correction) was performed. Graphs and significance annotations were prepared in RStudio (v2023.03.0 + 386) and GraphPad Prism v9.

3. Results

3.1. Uptake and internal translocation of PVC and PP NPs in plants

NP accumulation was evident across all three crop species, but the extent and redistribution patterns varied (Fig. 1). As expected, roots consistently served as the main reservoir for both PVC and PP, whereas only a small fraction was translocated to above-ground tissues. Plant species was the dominant factor determining translocation, with carrot accumulating the highest concentrations in shoots, followed by lettuce, and wheat displaying the lowest accumulation. There were limited differences between these two NP particles, with PVC generally accumulated at slightly higher levels than PP across tissues (Fig. 1).

When expressed as total NP mass per tissue, calculated by multiplying the NP concentration (mg NP kg^{-1} dry weight) by the corresponding tissue dry weight, the same species-specific pattern was observed. Roots were again the major sink across species: relative to carrot (100%), lettuce roots reached 49.7–99.6% (median $\sim 90.4\%$) and wheat 35.8–97.2% (median $\sim 60.2\%$), indicating broadly comparable root loads. In shoots, clear differences in total NP mass emerged: lettuce achieved 29.3–45.8% of carrot (median $\sim 34.9\%$), whereas wheat reached only 10.1–34.3% (median $\sim 20.0\%$). Species effects were significant ($p < 0.001$).

Direct comparison at the highest exposure level confirmed these patterns (Fig. 2). Carrot and lettuce accumulated broadly similar amounts of NPs in their roots, while wheat was comparable in case of PVC but contained nearly 50% less than carrot in case of exposure to PP (Fig. 2A). In shoots, however, the differences were striking: carrot contained the highest loads, with NP concentrations ~ 3 -fold greater than in lettuce and up to 8–10 times higher than in wheat (Fig. 2B). Lettuce maintained levels that were, consistently 2–3 times higher than wheat internal levels. These quantitative contrasts underline that plant species identity, rather than differences between these two NP particles

alone, was the more dominant factor to explain the distribution of NPs in plant tissues.

Translocation factors further illustrated these species-specific contrasts (Fig. 3). Carrot consistently exhibited the highest TF values, remaining in the range of approximately 2–4% across exposure concentrations, and reaching 3.9% (PVC) and 2.7% (PP) at the highest exposure level (Fig. 3A). Lettuce showed moderate and relatively stable TF values of around 1%, with PVC slightly exceeding PP at 5000 $\mu\text{g}\cdot\text{L}^{-1}$ (Fig. 3B). Wheat displayed the lowest TF values and the largest relative variation across treatments: while PP reached 1.7% at 500 $\mu\text{g}\cdot\text{L}^{-1}$, TF values at 5000 $\mu\text{g}\cdot\text{L}^{-1}$ decreased to approximately 0.6%, suggesting a non-monotonic response and limited root-to-shoot redistribution under the highest PP exposure (Fig. 3C). A direct comparison at the highest exposure level (Fig. 3D) highlighted pronounced differences among species: carrot translocated 2–3 times more than lettuce and 4–9 times more than wheat, while lettuce still exceeded wheat by up to 3-fold. The consistent order-of-magnitude differences in translocation among crop species indicate that plant species identity plays a key role in shaping NP redistribution within plants. In addition, TF values for PVC were generally higher than those for PP, suggesting particle-type-related differences in root-to-shoot translocation under the tested conditions, without allowing polymer chemistry to be isolated from size- or aggregation-related effects.

In summary, all three crop species took up PVC and PP NPs, yet their redistribution patterns differed significantly. Carrot combined substantial root accumulation with the highest relative extent of root-to-shoot translocation, reaching several-fold higher shoot loads than the other species. Lettuce accumulated root NP loads comparable to carrot, but its shoot loads were much lower. Wheat accumulated large amounts of NPs in roots but translocated the smallest fraction to the above ground tissues, reflecting strong below-ground confinement. Both concentration- and mass-based comparisons converge on the same conclusion.

3.2. Effects of PVC and PP NPs on plant growth parameters

Overall, growth responses were species dependent. Lettuce showed clear shifts in biomass allocation across treatments, with no consistent concentration-dependent trend, whereas carrot and wheat remained largely unaffected (Fig. 4; Table 1).

In lettuce, NP treatment consistently increased shoot dry mass while simultaneously suppressing root dry mass. Across the three exposure levels, PVC increased shoot dry weight by 30–50% and PP by 44–53% relative to the control ($p < 0.001$ for all comparisons; Fig. 4C). The converse pattern was observed below-ground: PVC reduced root dry

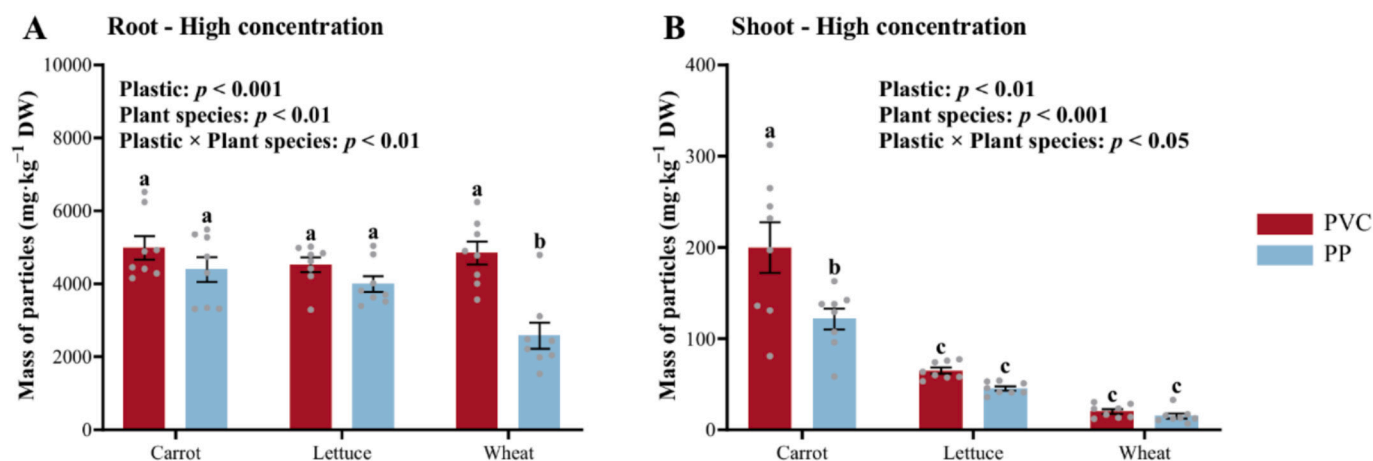


Fig. 2. Mass of particles (mean $\pm$ SE, expressed as $\text{g}\cdot\text{kg}^{-1}$ dry weight, DW) in roots (A) and shoots (B) of carrot (*Daucus carota*), lettuce (*Lactuca sativa*), and wheat (*Triticum aestivum*) after 14 days of hydroponic exposure to the highest concentration (5000 $\mu\text{g}\cdot\text{L}^{-1}$) of PVC-Gd and PP-Gd NPs. Two-way ANOVA results for the effects of plastic type, plant species, and their interaction are shown within each panel. Different letters above bars indicate significant differences between treatments (one-way ANOVA followed by Tukey's post-hoc test, $p < 0.05$). Error bars represent standard errors.

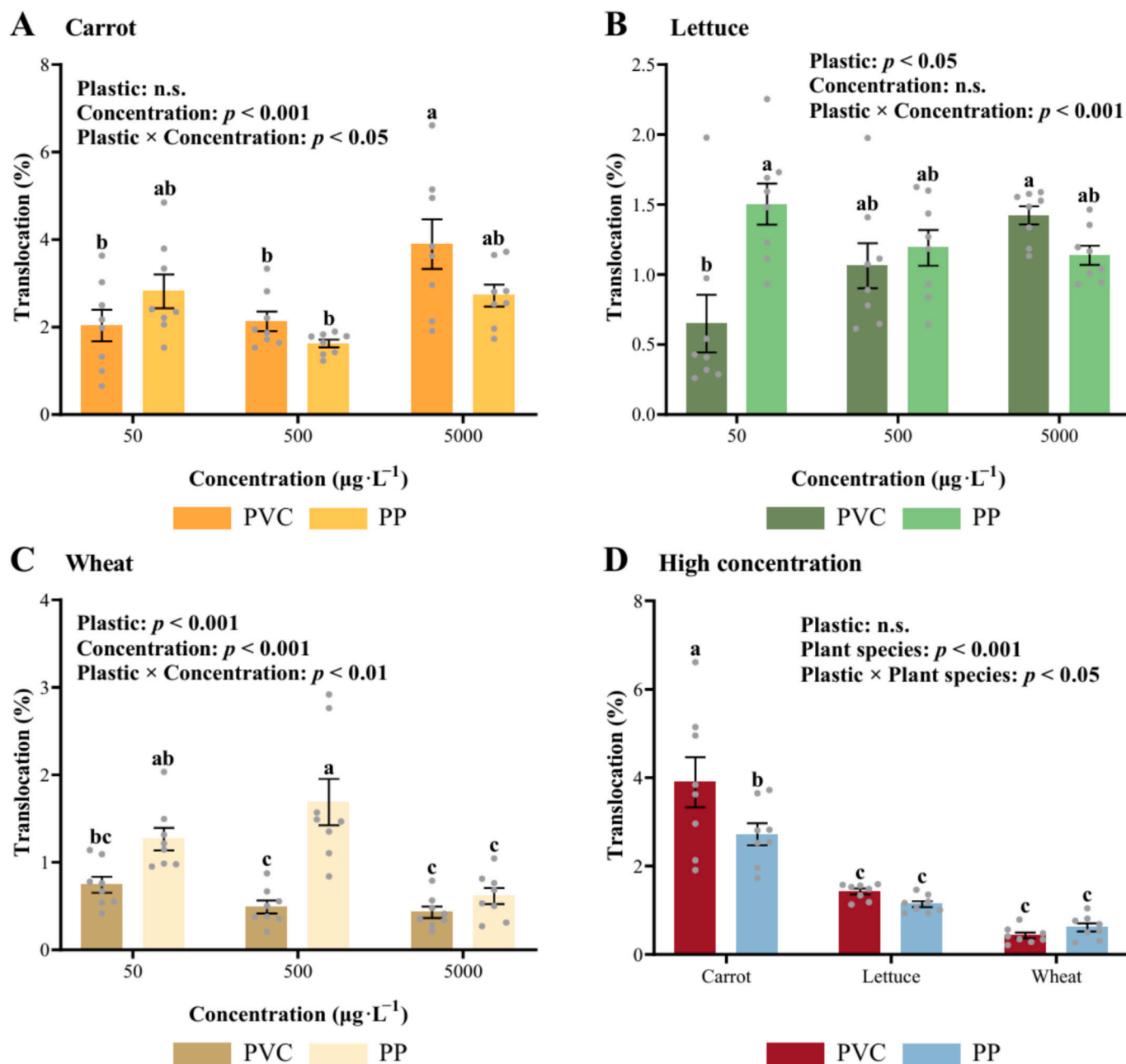


Fig. 3. Translocation factors (mean $\pm$ SE, %) of NP particles from roots to shoots in carrot (*Daucus carota*, A), lettuce (*Lactuca sativa*, B), and wheat (*Triticum aestivum*, C) after 14 days of hydroponic exposure to three concentrations (50, 500, and 5000 $\mu\text{g}\cdot\text{L}^{-1}$) of PVC-Gd and PP-Gd nanoplastics. Panel D shows species-specific comparisons under the highest exposure level (5000 $\mu\text{g}\cdot\text{L}^{-1}$). Two-way ANOVA results for the effects of plastic type, concentration, and plant species are shown within each panel. Different letters above bars indicate significant differences between treatments within species (one-way ANOVA followed by Tukey's post-hoc test, $p < 0.05$); n.s. indicates no statistically significant difference. Error bars represent standard errors.

weight by 31–36%, and PP by about one-third at the lowest and highest doses ($p < 0.05$; Fig. 4D). Shoot length responded only to the lowest PP concentration, rising by 14% ($p < 0.01$; Table 1), while root length remained statistically unchanged after post-hoc testing.

Carrot plants showed only minor changes in growth across most treatments. Shoot length, root length, and both fresh-mass endpoints did not differ from the control ($p > 0.05$; Table 1). A single effect emerged at the medium PVC dose, where shoot dry mass declined by 38% ($p = 0.04$; Fig. 4A). However, no other concentration of PVC, nor any PP treatment, produced a similar response. Root dry mass showed an overall significant p -value, yet post-hoc comparisons revealed no group differing from the control. Wheat likewise did not show clear responses to exposure, regardless of concentration. Shoot dimensions and all biomass variables

were statistically unchanged, except for root length, which increased by 26% at 5000 $\mu\text{g}\cdot\text{L}^{-1}$ PVC ($p = 0.03$; Table 1).

4. Discussion

Our findings show that: (i) all three species accumulated both types of NPs, with roots serving as the primary reservoir; (ii) PVC was generally accumulated and translocated at higher levels than PP, although this difference cannot be attributed to polymer chemistry alone; (iii) translocation was strongly species-specific, with carrot showing the highest root-to-shoot redistribution of the NPs; and (iiii) growth responses were species-dependent, as lettuce displayed a clear reallocation of biomass from roots to shoots, while carrot and wheat

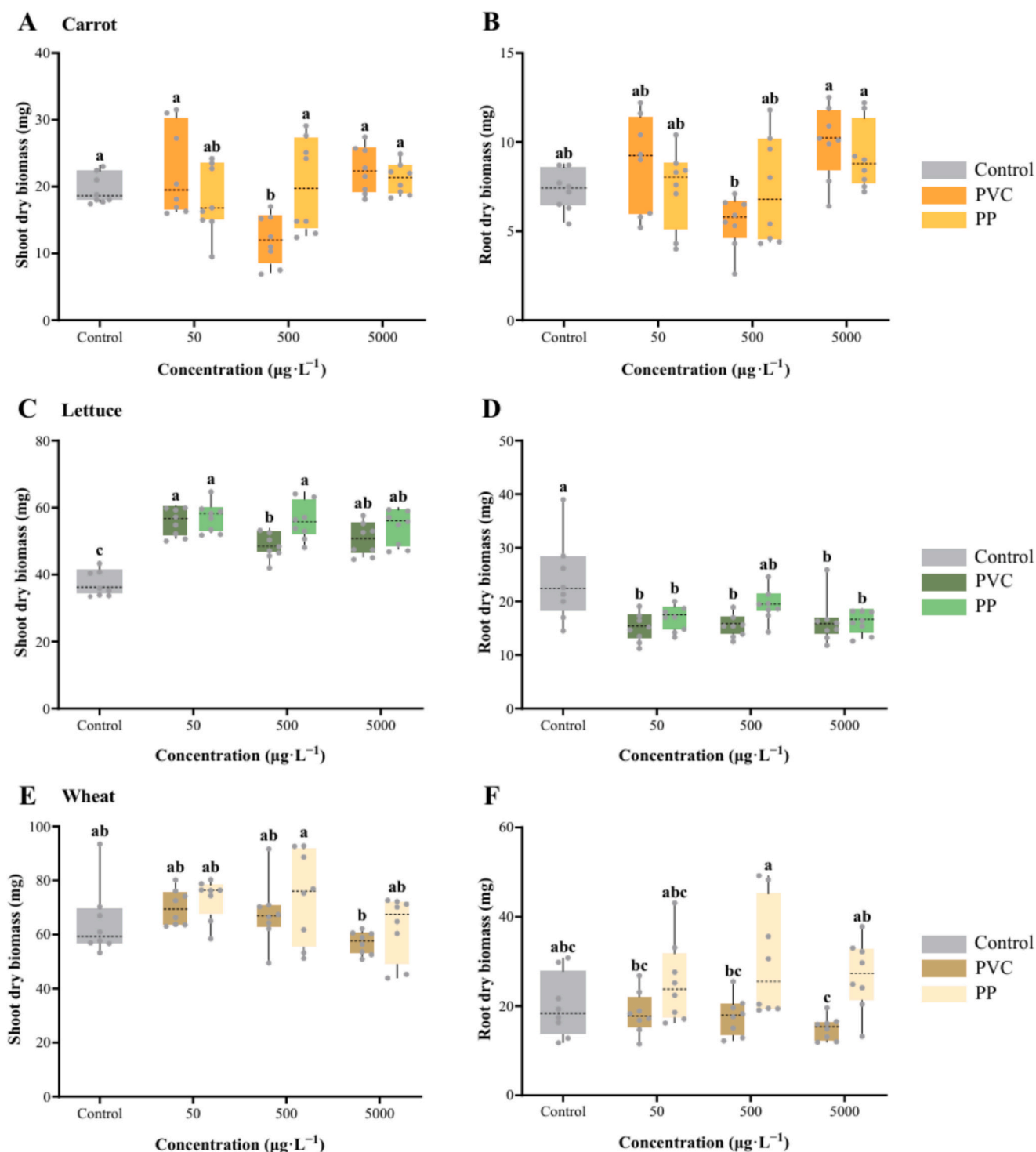


Fig. 4. Shoot dry biomass (A, C, E) and root dry biomass (B, D, F) of carrot (*Daucus carota*), lettuce (*Lactuca sativa*), and wheat (*Triticum aestivum*) after 14 days of hydroponic exposure to three concentrations (50, 500, and 5000 $\mu\text{g}\cdot\text{L}^{-1}$) of PVC-Gd and PP-Gd NPs, together with an unexposed control. Boxplots show medians, interquartile ranges, and data ranges. Different letters above boxplots indicate significant differences between treatments within species (one-way ANOVA followed by Tukey's post-hoc test, $p < 0.05$).

were largely unaffected. Together, these results indicate that crop species differ markedly in their capacity to take up and redistribute NPs, highlighting the need for further research on whether such uptake potential translates into accumulation in edible tissues under realistic agricultural exposure conditions. In the following sections, we discuss each of the four direct observations supported by the present dataset, and then explicitly distinguish them from possible physiological

explanations that remain hypothetical because root anatomy, transpiration, xylem fluxes, aquaporin activity, hormone balance, and molecular stress responses were not directly measured.

Our first observation was that roots were the primary reservoir of NPs. In this study, we demonstrated that all three crop species accumulated NPs, with roots serving as the primary reservoir and only minor fractions translocated to aerial tissues. Consistent with our observations,

Table 1

Shoot length, shoot fresh biomass, root length, and root fresh biomass of carrot (*Daucus carota*), lettuce (*Lactuca sativa*), and wheat (*Triticum aestivum*) after 14 days of hydroponic exposure to three concentrations (50, 500, and 5000 $\mu\text{g}\cdot\text{L}^{-1}$) of PVC-Gd and PP-Gd NPs, together with an unexposed control. Values are mean $\pm$ SE. Different letters indicate significant differences among treatments within each species and variable where significant treatment effects were detected (one-way ANOVA followed by Tukey's post-hoc test, $p < 0.05$). The absence of letters indicates no significant difference among treatments within that species and variable.

Plant species	Concentration ($\mu\text{g}/\text{L}$)	Shoot length (cm)	Root length (cm)	Shoot fresh biomass (mg)	Root fresh biomass (mg)
Carrot	Control	10.12 $\pm$ 0.58 ab	11.31 $\pm$ 1.67	119.4 $\pm$ 7.8 ab	86.8 $\pm$ 8.0
	PVC 50	10.61 $\pm$ 0.44 ab	7.58 $\pm$ 0.65	133.3 $\pm$ 13.8 ab	73.7 $\pm$ 10.2
	PVC 500	9.00 $\pm$ 0.49 b	7.51 $\pm$ 0.86	95.2 $\pm$ 10.6 b	51.2 $\pm$ 5.7
	PVC 5000	11.00 $\pm$ 0.34 a	9.90 $\pm$ 1.49	150.9 $\pm$ 11.2 a	87.3 $\pm$ 7.9
	PP 50	9.81 $\pm$ 0.23 ab	6.93 $\pm$ 1.20	120.4 $\pm$ 12.3 ab	58.7 $\pm$ 11.7
	PP 500	9.33 $\pm$ 0.62 ab	6.93 $\pm$ 1.08	117.8 $\pm$ 17.2 ab	73.1 $\pm$ 15.4
	PP 5000	10.03 $\pm$ 0.22 ab	9.48 $\pm$ 1.57	120.6 $\pm$ 5.5 ab	80.6 $\pm$ 8.5
	Control	5.88 $\pm$ 0.10 bc	12.14 $\pm$ 0.37	336.0 $\pm$ 11.6 b	203.8 $\pm$ 13.0 bc
	PVC 50	6.10 $\pm$ 0.21 ab	10.46 $\pm$ 0.47	456.9 $\pm$ 7.7 a	188.7 $\pm$ 3.8 c
	PVC 500	5.40 $\pm$ 0.17 c	10.59 $\pm$ 0.59	447.9 $\pm$ 6.9 a	178.5 $\pm$ 9.2 c
	PVC 5000	5.94 $\pm$ 0.11 bc	10.34 $\pm$ 0.53	475.1 $\pm$ 8.3 a	189.7 $\pm$ 8.8 c
	PP 50	6.71 $\pm$ 0.11 a	11.56 $\pm$ 0.45	477.9 $\pm$ 10.1 a	228.0 $\pm$ 7.6 ab
	PP 500	6.12 $\pm$ 0.16 ab	11.33 $\pm$ 0.27	476.2 $\pm$ 8.7 a	253.8 $\pm$ 8.1 a
	PP 5000	6.03 $\pm$ 0.17 bc	10.37 $\pm$ 0.38	436.1 $\pm$ 13.7 a	190.4 $\pm$ 7.1 c
	Control	22.39 $\pm$ 1.09	14.92 $\pm$ 0.83 b	340.9 $\pm$ 29.5	212.8 $\pm$ 26.8 ab
	PVC 50	22.15 $\pm$ 0.85	15.81 $\pm$ 0.74 ab	395.7 $\pm$ 9.7	234.1 $\pm$ 18.8 ab
Wheat	PVC 500	23.52 $\pm$ 0.86	16.97 $\pm$ 0.87 ab	359.5 $\pm$ 22.1	201.0 $\pm$ 15.4 b
	PVC 5000	20.66 $\pm$ 1.38	18.78 $\pm$ 1.10 a	354.5 $\pm$ 16.1	220.9 $\pm$ 11.3 ab
	PP 50	23.61 $\pm$ 0.68	15.95 $\pm$ 0.87 ab	408.0 $\pm$ 16.5	270.9 $\pm$ 30.3 ab
	PP 500	21.45 $\pm$ 1.47	14.97 $\pm$ 0.56 b	392.3 $\pm$ 34.0	312.1 $\pm$ 33.4 a
	PP 5000	21.52 $\pm$ 1.92	13.51 $\pm$ 0.79 b	356.6 $\pm$ 31.1	251.8 $\pm$ 23.3 ab

previous studies also report strong root retention of NPs across plant species, with only limited translocation to shoots [31,38,39]. Together with these previous observations, our findings reinforce that roots commonly act as the primary accumulation sites for NPs. However, the extent to which particles are transferred to aerial tissues remains contingent on particle properties, including polymer type, size, as well as plant species, and is therefore typically limited but not uniform across systems.

A key limitation of this observation is that ICP-MS quantification does not resolve particle localization within roots. The ICP-MS approach used here provides quantitative information on total Gd-labelled NP accumulation in digested plant tissues, but does not resolve the exact spatial location of particles within the root system. Therefore, the root-associated NP signal may include both particles internalized into root tissues and particles strongly adsorbed to the root surface or retained within root mucilage and surface structures. Although the standardized rinsing procedure was applied to reduce loosely attached external

particles (e.g., see [24,26]), complete removal of strongly bound particles cannot be guaranteed. Accordingly, root accumulation in this study should be interpreted as root-associated NP enrichment rather than direct evidence of complete cellular internalization. In contrast, the detection of NPs in shoot tissues indicates that at least a fraction of the particles crossed the root barrier and entered internal transport pathways. Previous imaging-based studies have shown that fluorescently labelled NPs can be detected in cortical regions and, in some cases, vascular tissues of plant roots, supporting the possibility of internal localization and subsequent redistribution [40]. However, future studies combining quantitative tracer analysis with confocal microscopy, electron microscopy, or cross-sectional imaging are needed to distinguish surface adsorption, apoplastic localization, and cellular internalization more directly.

Our second key observation was that PVC NPs generally showed higher accumulation and translocation than PP NPs. This pattern should be interpreted as a particle-type-related difference rather than as direct evidence of a polymer-chemistry effect. PVC and PP differed not only in polymer composition, but also in hydrodynamic size and aggregation behavior. PVC had a smaller initial hydrodynamic diameter than PP, and the additional 7-day MADLS measurements in Hoagland solution showed aggregation for both particle types, particularly for PP. Therefore, the higher accumulation and translocation observed for PVC should be interpreted as a particle-type-related pattern reflecting the combined influence of polymer composition, particle size, surface properties, and aggregation behavior, rather than as an effect of polymer chemistry alone.

There are several possible explanations for the higher uptake of PVC NPs. Differences in particle size, surface properties, and aggregation behavior may influence particle availability, root association, and root-to-shoot redistribution. Previous studies have shown that particle size, surface properties, and aggregation behavior can affect how NPs enter and move through root tissues, influencing processes such as endocytosis, apoplastic transport, or crack entry [18,41]. Previous studies have also reported size-dependent NP uptake and tissue distribution in plants, with smaller PS-NPs generally showing greater potential for root entry and deeper tissue penetration than larger particles [42,43]. Surface charge-related characteristics and surface functional groups can affect colloidal stability, aggregation, and dispersion behavior [44], which may in turn influence particle availability and transport. However, in the present study, the difference in zeta potential between PVC and PP was relatively small (-8.65 mV vs. -11.72 mV), and therefore surface charge alone is unlikely to explain the observed differences between these two NP particles. Structural characteristics of the polymer may further modulate plant-particle interactions, and the polarity associated with C–Cl bonds in PVC has been suggested to enhance interactions with cell wall components, potentially promoting retention or internalization [45]. However, this explanation remains hypothetical in the present study, because polymer chemistry cannot be separated from the differences in size and aggregation behavior between PVC and PP. Overall, differences between these two NP particles should be interpreted cautiously and are likely to reflect the combined influence of particle size, surface properties, aggregation behavior, and polymer chemistry.

A third key observation was that the root-to-shoot redistribution was strongly species-specific. Carrot showed the highest TF values, lettuce showed intermediate values, and wheat showed the lowest values. This pattern was evident despite all three species being exposed under the same hydroponic conditions, indicating that plant species identity was a major factor shaping NP redistribution in the tested system. However, the present study does not directly identify the physiological mechanisms responsible for these species-specific differences.

Possible explanations for the species-specific differences in root-to-shoot redistribution include differences in root anatomy, vascular accessibility, transpiration-related water fluxes, and biomass allocation. Previous studies suggest that anatomical and physiological traits may

influence NP uptake and distribution. For example, taproot systems of dicots such as carrot and lettuce contain more lateral root junctions that may act as entry points, whereas cereals like wheat often develop stronger endodermal barriers, including lignified Casparian strips, that restrict apoplastic movement [42,46]. Likewise, species with higher transpiration rates can generate stronger upward water flow, which may enhance xylem loading and particle delivery to aerial tissues [47]. Aquaporins have also been implicated in regulating water and solute transport; therefore, variation in aquaporin activity represents a possible, but untested, contributor to interspecific differences in NP translocation [48]. Although carrot and lettuce are both dicot species, the substantially higher TF observed in carrot indicates that broad taxonomic categories alone are insufficient to explain NP redistribution patterns. Instead, finer-scale species traits, including root architecture, vascular accessibility, transpiration-related water fluxes, and biomass allocation, may act together to influence NP uptake and translocation. Rather than acting independently, these traits may form coordinated plant functional trait combinations that together influence particle entry, retention, and redistribution. For example, root morphology may influence the number and location of potential entry points, whereas vascular organization and transpiration-driven water flow may affect whether particles that reach internal tissues are retained in roots or transported towards shoots [49,50]. Carrot develops a pronounced storage taproot with secondary growth and extensive vascular tissues, which could affect radial transport pathways and the accessibility of vascular tissues for NPs [51]. A recent imaging-based study has shown that fluorescently labelled NPs can enter root tissues of carrot and lettuce, with particles observed in cortical regions and, in some cases, vascular tissues [40]. These observations support the possibility that tissue-level localization and vascular accessibility may contribute to species-specific NP redistribution. In addition, despite substantial carbon allocation to belowground storage, carrot maintains an active and functional shoot system during vegetative growth, which may imply sustained transpiration and upward water fluxes that may facilitate passive root-to-shoot transport [18]. Thus, the comparatively higher TF in carrot may be associated with the combined influence of storage-root anatomy, vascular accessibility, root–shoot physiological connectivity, and transpiration-driven xylem flow, rather than the effect of any single trait alone [52]. In contrast, lettuce exhibits a relatively shallow and fibrous root system with rapid turnover, which may favor retention of particles in root tissues rather than sustained vascular redistribution [53]. Functional differences between storage-root crops and leafy vegetables may further influence internal allocation dynamics, as carrot roots remain physiologically connected to shoot growth during early vegetative development, whereas lettuce primarily allocates resources towards rapid leaf expansion [54]. Together, these findings suggest that species traits, including root anatomy and internal water transport dynamics, may interact to shape the internal movement of NPs, although this hypothesis requires further investigation. Because carrot, lettuce, and wheat differ in inherent growth rate, developmental trajectory, and biomass allocation strategy, growth-stage-related differences cannot be fully excluded as contributors to the observed species-specific patterns, even though all plants were exposed during the seedling/early vegetative stage under standardized conditions [55]. Future research should examine whether species-specific transport patterns correspond to differences in xylem fluxes, root anatomical traits, tissue partitioning, and whole-plant allocation strategies, and whether these routes determine NP accumulation in edible plant parts.

A fourth key observation was that growth responses were species-dependent and did not correspond directly to translocation magnitude. We observed effects on plant performance following NP exposure; however, these results should be interpreted with caution, as the relatively high concentrations were selected to enable reliable particle tracking, and not to mimic environmentally realistic concentrations. Lettuce showed clear treatment-related shifts in biomass allocation under both PVC and PP exposure. While carrot and wheat showed little

change, again suggesting that crop species may be more influential than polymer type in determining growth responses.

This lettuce-specific response may depend on species-specific sensitivity, root-localized particle interactions, internal stress signaling, and biomass allocation strategies. Lettuce showed clear treatment-related shifts in biomass allocation under both PVC and PP exposure, but these responses were not consistently dose-dependent. A similarly strong yet opposite pattern was reported by Li et al. [25], who observed a 36% reduction in lettuce shoot biomass after 21 d exposure to 1000 mg·L⁻¹ PS-NPs in Hoagland medium, while root biomass remained unchanged. In contrast, a recent systematic review by Zantis et al. [17] emphasized that plant responses to MNPs vary considerably across species and experimental setups, with reports ranging from growth stimulation to clear inhibitory effects. Taken together, these studies indicate that (i) lettuce is consistently sensitive to NPs, but (ii) the direction and magnitude of the biomass shift may depend on particle properties and growth matrix. Our finding of shoot stimulation coupled with root inhibition suggests a resource reallocation towards aerial tissues under PVC and PP NP stress, although the underlying mechanisms cannot be resolved from the present dataset. One possible explanation is that NP exposure altered endogenous hormone balance, particularly auxin-, cytokinin-, ethylene-, or abscisic-acid-related signaling pathways, which are known to regulate root growth, shoot development, and biomass partitioning [56]. A reduction in root biomass together with maintained or enhanced shoot growth could also reflect changes in nutrient acquisition and allocation under hydroponic conditions, where nutrients are directly available in solution and plants may sustain shoot expansion despite reduced root investment [57]. In addition, NP exposure may have triggered stress-response pathways, including oxidative stress signaling or cell-wall-related responses, that preferentially constrained root growth while allowing compensatory shoot growth [58]. Importantly, this growth response did not correspond directly to the magnitude of root-to-shoot translocation. Carrot showed the highest TF values but only minor growth changes, whereas lettuce showed the clearest biomass allocation response despite intermediate TF values. This mismatch suggests that plant performance effects are not determined simply by the fraction of particles translocated to shoots, but may depend more strongly on species-specific sensitivity, root-localized particle interactions, internal stress signaling, and growth allocation strategies [59]. In contrast, PS-NPs at very high levels appear to trigger overall growth suppression [25]. Because hormone concentrations, nutrient profiles, photosynthetic performance, and molecular stress markers were not measured in this study, these explanations should be regarded as hypotheses. Future studies should combine biomass measurements with analyses of hormone metabolism, nutrient transport, oxidative stress responses, and gene expression to determine whether these pathways regulate NP-induced biomass redistribution in lettuce. It is important to note that our study was conducted in hydroponics. In contrast, the soil-based growth enhancement reported by Zhang et al. [60] suggests that interactions with the soil matrix can mitigate or even reverse NP effects observed in solution culture.

To place our findings in context, we compared our results with previous studies on NP uptake and translocation in plants (Table 2), which have only focused on PS particles. Across these experiments, a consistent finding is that roots are the primary sink, while transfer to shoots varies widely across species and experimental setups. Reported shoot-to-root transfer factors (TF, harmonized to percent of root load) range from 0.1% in dandelion [61] and 0.6% in *Arabidopsis* [62] to 1.6–3.9% in carrot and 0.7–14% in lettuce [24,26,33], with wheat spanning a particularly broad interval from <1 up to 20% depending on exposure conditions [24,63,64]. Rice also showed moderate transfer (~5%) [39], whereas cucumber displayed negligible accumulation in shoots [65]. Such variation indicates that the extent of translocation is not consistently explained by plant type (monocot vs. dicot) but is instead highly species-specific and context-dependent. Although the number of available studies remains limited, this diversity underscores

Table 2

Summary of experimental studies investigating NP uptake, translocation, and effects in crop and model plants ($n = 10$ studies). Information includes plant type, species, exposure medium, polymer type and tracer, particle size, concentration, duration, uptake and translocation patterns, and observed effects. Abbreviations: DW, dry weight; Eu, europium; FW, fresh weight; Gd, gadolinium; NPs, nanoplastics; Pd, palladium; PP, polypropylene; PS, polystyrene; PVC, polyvinyl chloride; TF, translocation factor.

Plant type	Plant species	Medium	Polymer type & tracer	Size	Concentration	Duration	Uptake	Translocation (%)	Effects	Source
Monocot	Rice (<i>Oryza sativa</i>)	Hydroponic (Yoshida solution)	PS & Eu	~51 nm	0, 10,000, 50,000 $\mu\text{g}\cdot\text{L}^{-1}$	14 days	Root accumulation is dominant (93.6–95.0% of total load)	Shoot transfer TF = 5.2–5.3%	Growth inhibition ($\downarrow$ plant height, root length, DW)	[39]
	Wheat (<i>Triticum aestivum</i>)	Hydroponic (Hoagland solution)	PVC, PP & Gd	~257 nm (PVC), ~352 nm (PP)	50, 500, 5000 $\mu\text{g}\cdot\text{L}^{-1}$	14 days	Roots accumulated up to 4845 $\text{mg}\cdot\text{kg}^{-1}$ DW (at 5000 $\mu\text{g}\cdot\text{L}^{-1}$)	Shoot transfer TF = 0.4–1.7%	Minimal growth impact; slight root length $\uparrow$ 26% at 5000 $\mu\text{g}\cdot\text{L}^{-1}$ PVC	Our study
	Wheat (<i>Triticum aestivum</i>)	Stingal soil (PS-Pd NPs suspension irrigated)	PS & Pd	~68 nm	110,000 $\mu\text{g}\cdot\text{L}^{-1}$ (6.3×10^{14} NPs $\cdot\text{L}^{-1}$)	5 days (daily irrigation)	Roots: 13.13 $\pm$ 2.06 $\text{mg}\cdot\text{kg}^{-1}$ DW $\approx$ 1.52×10^{11} NPs $\cdot\text{g}^{-1}$	Shoots: 9.49 $\pm$ 0.56 $\text{mg}\cdot\text{kg}^{-1}$ DW $\approx$ 1.09×10^{11} NPs/g; ~75.7% of absorbed NPs translocated to shoots	Fresh biomass $\downarrow$ 77.3%; root/shoot length not significantly changed	[63]
	Wheat (<i>Triticum aestivum</i>)	Hydroponic (20% Hoagland solution)	PS & Eu	~244 nm	0, 5, 10, 100, 5000 $\mu\text{g}\cdot\text{L}^{-1}$	6 days	Roots: 1.3–1494 $\text{mg}\cdot\text{kg}^{-1}$ DW	Shoots: TF <3%	No significant effect on growth	[24]
	Wheat (<i>Triticum aestivum</i>)	Sandy soil	PS & Eu	~244 nm	1 & 10 $\text{mg}\cdot\text{kg}^{-1}$	14 days	Roots: 3.0–5.2 $\text{mg}\cdot\text{kg}^{-1}$ DW	Shoots: TF = 9%	No significant effect on growth	[24]
	Wheat (<i>Triticum aestivum</i>)	Hydroponic (1/4 Hoagland solution)	PS & Pd	~160 nm	3000 & 30,000 $\mu\text{g}\cdot\text{L}^{-1}$	21 days	Roots: 100–4800 $\text{mg}\cdot\text{kg}^{-1}$ DW	Shoots: 80–300 $\text{mg}\cdot\text{kg}^{-1}$ DW, TF = 6–20%	No biomass change	[64]
Dicot	<i>Arabidopsis thaliana</i>	Hydroponic (1/2 Hoagland solution)	PS-NPs doped with persistent luminescence nanoparticles (PS@PLNP, Cr^{3+} :ZnGa ₂ O ₄)	~216 nm	0, 5000, 50,000 $\mu\text{g}\cdot\text{L}^{-1}$	10 days	Roots: 910 $\text{mg}\cdot\text{kg}^{-1}$ DW (5000 $\mu\text{g}\cdot\text{L}^{-1}$); 3352 $\text{mg}\cdot\text{kg}^{-1}$ DW (50,000 $\mu\text{g}\cdot\text{L}^{-1}$)	Shoots: 5.011 $\text{mg}\cdot\text{kg}^{-1}$ DW (5000 $\mu\text{g}\cdot\text{L}^{-1}$); 7.885 $\text{mg}\cdot\text{kg}^{-1}$ DW (50,000 $\mu\text{g}\cdot\text{L}^{-1}$); TF = 0.55% (5000 $\mu\text{g}\cdot\text{L}^{-1}$), 0.24% (50,000 $\mu\text{g}\cdot\text{L}^{-1}$)	No significant phytotoxicity; root/shoot biomass unaffected up to 50,000 $\mu\text{g}\cdot\text{L}^{-1}$	[62]
	Carrot (<i>Daucus carota</i>)	Hydroponic (Hoagland solution)	PVC, PP & Gd	~257 nm (PVC), ~352 nm (PP)	50, 500, 5000 $\mu\text{g}\cdot\text{L}^{-1}$	14 days	Roots accumulated up to 4986 $\text{mg}\cdot\text{kg}^{-1}$ DW (at 5000 $\mu\text{g}\cdot\text{L}^{-1}$)	Shoot transfer TF = 1.6–3.9%	Growth largely stable; isolated shoot DW decline ($\downarrow$ 38% at 500 $\mu\text{g}\cdot\text{L}^{-1}$ PP)	Our study
	Cucumber (<i>Cucumis sativus</i>)	Hydroponic (1/2 Hoagland solution)	PS & Pd	~196 nm	5000 $\mu\text{g}\cdot\text{L}^{-1}$	4 days	Roots: ~1500 $\text{mg}\cdot\text{kg}^{-1}$ DW	Stems: ~25 $\text{mg}\cdot\text{kg}^{-1}$ DW; Leaves: not detected	No significant growth effects reported	[65]
	Dandelion (<i>Taraxacum mongolicum</i>)	Hydroponic (Hoagland solution)	PS & Eu	~100 nm	10,000 $\mu\text{g}\cdot\text{L}^{-1}$	5 days	Roots: 15 $\text{mg}\cdot\text{kg}^{-1}$ DW	Shoots: 0.015 $\text{mg}\cdot\text{kg}^{-1}$ DW, TF: 0.1%	Root cell wall deformation	[61]
	Lettuce (<i>Lactuca sativa</i>)	Hydroponic (Hoagland solution)	PVC, PP & Gd	~257 nm (PVC), ~352 nm (PP)	50, 500, 5000 $\mu\text{g}\cdot\text{L}^{-1}$	14 days	Roots accumulated up to 4523 $\text{mg}\cdot\text{kg}^{-1}$ DW (at 5000 $\mu\text{g}\cdot\text{L}^{-1}$)	Shoot transfer TF = 0.7–1.5%	Shoot biomass $\uparrow$ 30–53%, root biomass $\downarrow$ 31–36%	Our study
	Lettuce (<i>Lactuca sativa</i>)	Hydroponic (Hoagland solution)	PS & Eu	~100 nm	15, 150, 1500 $\mu\text{g}\cdot\text{L}^{-1}$	21 days	Roots: 3.8×10^{-4} , 4.8×10^{-3} , 3.2×10^{-2} $\text{mg}\cdot\text{kg}^{-1}$ DW ($\approx 6.9 \times 10^5$ – 5.7×10^7 particles)	Shoots: detected only at 1500 $\mu\text{g}\cdot\text{L}^{-1}$ (5.2×10^{-4} $\text{mg}\cdot\text{kg}^{-1}$ DW, $\approx 9.5 \times 10^5$ particles); TF $\approx$ 1.7% $\pm$ 5.7%	Root dry weight $\uparrow$ 65% at 1500 $\mu\text{g}\cdot\text{L}^{-1}$; no significant effects on shoots	[26]
	Lettuce (<i>Lactuca sativa</i>)	Foliar spray	PS & ^2H	~80 nm	100, 1000, 5000 $\mu\text{g}\cdot\text{L}^{-1}$ ($\approx$ 0.15, 1.5, 7.5 $\mu\text{g}\cdot\text{plant}^{-1}\cdot\text{day}^{-1}$)	7 days (daily spraying)	Leaves: 0.73 $\pm$ 0.22, 2.36 $\pm$ 0.24, 15.61 $\pm$	Roots: 0.007 $\pm$ 0.002, 0.11 $\pm$ 0.01, 0.21 $\pm$ 0.04 $\text{mg}\cdot\text{kg}^{-1}$	Slight reduction in shoot FW and plant height	[33]

(continued on next page)

Table 2 (continued)

Plant type	Plant species	Medium	Polymer type & tracer	Size	Concentration	Duration	Uptake	Translocation (%)	Effects	Source
	Lettuce (<i>Lactuca sativa</i>)	Hydroponic (20% Hoagland solution)	PS & Eu	~244 nm	0, 5, 10, 100, 5000 $\mu\text{g}\cdot\text{L}^{-1}$	6 days	3.21 $\text{mg}\cdot\text{kg}^{-1}$ DW Roots: 4.1–2220 $\text{mg}\cdot\text{kg}^{-1}$ DW	DW; leaf→root <5% Shoots: <3% of root load	No significant effect on growth	[24]
	Lettuce (<i>Lactuca sativa</i>)	Sandy soil	PS & Eu	~244 nm	1 & 10 $\text{mg}\cdot\text{kg}^{-1}$	14 days	Roots: 4.3–15.2 $\text{mg}\cdot\text{kg}^{-1}$ DW	Shoots: TF = 14%	No significant effect on growth	[24]

the need for mechanistic studies that link anatomical traits, transpiration strength, and stress physiology with observed transfer rates. Understanding these drivers will be important for predicting which crops are most likely to mobilize NPs to edible tissues.

From an applied perspective, and as a basis for future food-safety assessment, it is important to account for the edible parts of the plants in relation to uptake and translocation. For root vegetables such as carrot, follow-up studies should prioritize quantification in edible root tissues, which also represent the primary accumulation site. In leafy vegetables such as lettuce, above-ground tissues warrant greater attention, as even limited root-to-shoot transfer may be relevant for consumption. For cereals such as wheat, future work should focus on whether and to what extent NPs can reach reproductive tissues, particularly grains, as current evidence remains limited.

In summary, our study shows that NPs are consistently taken up by crop roots, but their upward transport is variable among species, with carrot mobilizing a larger fraction compared to lettuce and wheat. These findings indicate that, within the tested system, polymer identity (between PVC and PP) and size may play a role in accumulation, but that plant traits are likely more dominant factors shaping NP uptake and redistribution. It is important to emphasize that the exposure concentrations applied here exceed current estimates for agricultural environments and were selected to ensure analytical detectability and cross-species comparability under controlled conditions. Accordingly, the present findings should not be interpreted as direct evidence of field-relevant risk at environmentally realistic exposure levels, but rather as comparative insights into species- and polymer-dependent uptake and translocation behavior. Similarly, the observed accumulation in roots and shoots should not be directly extrapolated to food-safety risk under agricultural soil conditions, because soil matrices can substantially alter NP mobility, bioavailability, and plant exposure. In addition, the particles used in this study were pristine, commercially produced NP suspensions rather than environmentally aged particles. In agricultural environments, NPs may undergo surface oxidation, biofilm formation, and interactions with dissolved organic matter, soil minerals, root exudates, and microbial communities, which can modify particle size, surface chemistry, aggregation behavior, and bioavailability [66,67]. Therefore, the behavior of environmentally aged NPs may differ from the pristine tracer-labelled particles used here. Hydroponic experiments, therefore, serve as an important first step for understanding NP uptake and internal transport processes. Future studies should move towards experimental designs that better mimic agricultural soils, explicitly considering how particle properties such as size, surface charge, polymer chemistry, and ageing status interact with soil matrices, organic matter, and microbial communities to determine bioavailability. Future work should therefore disentangle how particle traits and exposure media jointly modulate crop physiology, and whether above-ground accumulation could affect edible tissues under more realistic exposure scenarios. However, quantitative food-safety or human-exposure implications require further soil-based studies combined with measurements in edible organs and dietary exposure assessment. Integrating plant physiology with soil science, ecotoxicology, and food safety research will be essential to predict which crops may be more

susceptible to NP exposure under real-world farming conditions.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used ChatGPT in order to aid in the writing process and to get a more cohesive language throughout the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Peiyan Qin: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jildou Dijkstra:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Adriaan J.A. Duijndam:** Writing – review & editing, Writing – original draft, Investigation. **Christia R. Jabbour:** Writing – review & editing, Resources. **Laurens D. B. Mandemaker:** Writing – review & editing, Validation, Resources, Project administration. **Florian Meirer:** Writing – review & editing, Supervision. **Willie J.G.M. Peijnenburg:** Writing – review & editing, Supervision, Conceptualization. **Martina G. Vijver:** Writing – review & editing, Supervision, Conceptualization. **Thijs Bosker:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Funding

LDBM, FM, WJGMP, MG, and TB were funded by the Netherlands Organization for Health Research and Development (ZonMw) through the MOMENTUM program (breakthrough project “Food for Thought”, project number 04580012320002).

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Thijs Bosker, Laurens D. B. Mandemaker, Florian Meirer, Martina G. Vijver, and Willie Peijnenburg report that the Netherlands Organization for Health Research and Development (ZonMw) provided financial support. Peiyan Qin reports that the China Scholarship Council (CSC) provided financial support. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank M. Wang, T. Nederstigt, and L.J. Zantis for their guidance and technical support on experimental protocols. We are grateful to K. Serwatowska and E. Hoogwout for their assistance with laboratory facilities and equipment. The authors also

thank F. Al Manji and S. Zheng for their help with ICP–MS measurements. The graphical abstract was created with BioRender.com.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.enceco.2026.06.007>.

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