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REVIEW ARTICLE

# Breaching the Root Barrier: Uptake Pathways, Rhizosphere Microenvironment Regulation, and Physiological Metabolic Responses of Rice to Nanomaterials

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**ABSTRACT:** The rapid advancement of nanotechnology, coupled with the exacerbation of plastic pollution, has positioned the continuous accumulation of nanoparticles (NPs) and micro/nanoplastics (MNPs) in agricultural soils as a critical global concern. As one of the world's primary staple crops, the root system of rice (Oryza sativa L.) serves as the initial line of defense and response against nano-pollutants. The multidimensional interaction mechanisms of NPs within complex soil-rice systems, however, remain insufficiently elucidated. This review comprehensively synthesizes the interfacial interactions between NPs and rice roots, their uptake and translocation pathways, and the dual biological effects they induce. The assimilation and systemic translocation of NPs are dynamically governed by particle physicochemical traits (e.g., size, surface charge, and coating chemistry) and rice-specific rhizosphere modulators, notably the iron plaque and root exudates. It is particularly noteworthy that NPs exhibit a pronounced "double-edged sword" effect on rice: rationally designed nano-agrochemicals can function as elicitors to activate plant defense systems and effectively immobilize heavy metals. Conversely, emerging nanoplastics induce severe oxidative stress and metabolic disruption. Furthermore, these particles act as potent vectors, utilizing a "Trojan horse" mechanism to facilitate the co-transport of heavy metals and agrochemicals, thereby breaching root barriers and exacerbating dietary exposure risks. To systematically bridge existing knowledge gaps, we propose a comprehensive research roadmap emphasizing realistic field exposures, soil-rice-microbiome coupling, combined pollution dynamics, in planta quantification, and grain bioaccessibility assessments. This holistic paradigm ultimately provides robust scientific substantiation for the risk assessment of nano-pollutants and the promotion of sustainable nano-agriculture.

**Keywords:** Root barrier; Uptake pathways, Rhizosphere microenvironment; Rice; Nanomaterials, Plastic pollution.

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## 1. INTRODUCTION

To place rice exposure within a broader paddy-field context, it is necessary to connect exogenous NP/MNP inputs with their environmental transformations, plant entry routes, and eventual food-chain implications. As illustrated in Figure 1, the behavior of NPs/MNPs in rice systems should be interpreted as a continuous process spanning source input, rhizosphere transformation, plant uptake, grain transfer, and dietary exposure risk. Nanoparticles (NPs) are generally defined as materials with at least one dimension measuring less than 100 nm. Characterized by high specific surface areas, elevated surface reactivities, and size-dependent properties distinct from bulk materials, various engineered

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nanomaterials have been extensively developed for agricultural inputs and environmental remediation, encompassing nano-fertilizers, nano-pesticides, and contaminant passivators [1-4]. The accelerated industrialization of nanotechnology, compounded by multiple inputs, including the degradation of agricultural plastic films, biosolid application, reclaimed water irrigation, and industrial emissions, has precipitated the continuous influx of engineered nanomaterials and micro/nanoplastics (MNPs) into agroecosystems, rendering them emerging contaminants of profound global concern [3,5].

Agricultural soils are recognized as primary environmental sinks for diverse nano-pollutants. As primary producers in terrestrial ecosystems and the foundational trophic level of the food web, plants are inevitably subjected to chronic exposure within these intricate nano-environments. Extant literature indicates that the dynamics of NPs within the soil-plant continuum manifest a pronounced "double-edged sword" paradigm: on one end of the spectrum, certain nanomaterials, administered at appropriate dosages and possessing optimal physicochemical properties, can enhance nutrient utilization, modulate rhizosphere processes, and fortify plant stress tolerance, even mitigating the translocation of contaminants such as Cd and As to rice grains.

Conversely, excessive exposure or highly bioavailable nanomaterials, particularly those with diminutive dimensions and heightened surface activities, possess the propensity to breach root surfaces and cellular barriers, translocating and accumulating within root, stem, and leaf tissues. This accumulation frequently precipitates the excessive generation of reactive oxygen species (ROS), impairs photosynthetic apparatuses, and induces metabolic perturbations, ultimately disrupting soil physicochemical attributes and the structural integrity of rhizosphere microbial communities [2, 4, 6-9].

For staple crops like rice and wheat, the assimilation and cross-tissue translocation of NPs, alongside their subsequent impacts on edible plant parts, warrant particular scrutiny due to their direct implications for crop ontogeny, yield formation, and food safety. Evidence indicates that polystyrene nanoplastics and microplastics can be assimilated by rice roots and translocated to aerial tissues. Specific nanomaterials may additionally modulate the accumulation of elements like Cd and As in grains by altering contaminant bioavailability in paddy soils, modifying root iron plaque formation, and influencing internal plant transport mechanisms [7, 8, 10]. Crucially, beyond their direct independent effects, high-surface-area NPs and MNPs function as potent vectors for co-contaminants. By adsorbing heavy metals and agrochemicals, they elicit an insidious "Trojan horse" effect that facilitates the breaching of root barriers, thereby escalating the potential risk of pollutant migration and biomagnification along the soil-crop-human continuum [5, 7, 10].

Although investigations into the phytotoxicity of individual nanomaterial types are proliferating, a systematic synthesis of the multidimensional interaction mechanisms of NPs within complex soil-plant systems remains conspicuously absent, particularly regarding the continuity from rhizosphere environmental alterations and plant uptake behaviors to physiological, biochemical, and molecular responses [2, 4, 6].

Consequently, focusing on staple crops such as rice, this review systematically dissects the uptake, cross-media translocation, and accumulation mechanisms of NPs in planta. It elucidates the physiological, biochemical, and molecular foundations underlying their induced toxicity or stress-resistance effects, and delineates their indirect ecological impacts on soil physicochemical properties and rhizosphere microbial assemblages, aiming to provide a robust scientific basis for the risk assessment of agricultural nanomaterial applications and the safeguarding of global food security. Crucially, to systematically bridge the identified knowledge gaps, this review culminates in a comprehensive, forward-looking research roadmap. This roadmap highlights five pivotal directions, ranging from realistic field exposures to dietary risk assessments, designed to guide the next generation of sustainable nano-agricultural interventions.

To place rice exposure within a broader paddy-field context, it is necessary to connect exogenous NP/MNP inputs with their environmental transformations, plant entry routes, and eventual food-chain implications. As illustrated in Figure 1, the behavior of NPs/MNPs in rice systems should be interpreted as a continuous process spanning source input, rhizosphere transformation, plant uptake, grain transfer, and dietary exposure risk [2, 4, 6].

## 2. UPTAKE AND TRANSLOCATION MECHANISMS OF NANOPARTICLES IN PLANTS

The uptake, accumulation, and long-distance translocation of NPs within plants are co-regulated by their intrinsic physicochemical properties (e.g., particle size, morphology, surface charge, coatings, and solubility), as well as by the plant species, anatomical structures, and the exposure environment. Thus, elucidating the migration pathways of NPs within the soil-plant continuum constitutes a fundamental prerequisite for evaluating their potential phyto-effects and food chain transfer risks. It is generally established that plant assimilation of NPs occurs primarily via two portals: foliar exposure, whereby particles penetrate leaf tissues through epidermal structures, cuticular micro-defects, or stomata, occasionally undergoing subsequent phloem loading for systemic redistribution; and rhizosphere contact, where NPs traverse the root surface into internal tissues, followed by upward transport via the xylem. These pathways are not mutually exclusive but interactively form the holistic translocation network of nanomaterials in planta [4, 11, 12]. To visually delineate the principal entry routes, barrier penetration processes, and long-distance transport networks of NPs in rice, Figure 2 summarizes the foliar and root uptake pathways alongside their critical interfacial regulatory nodes.


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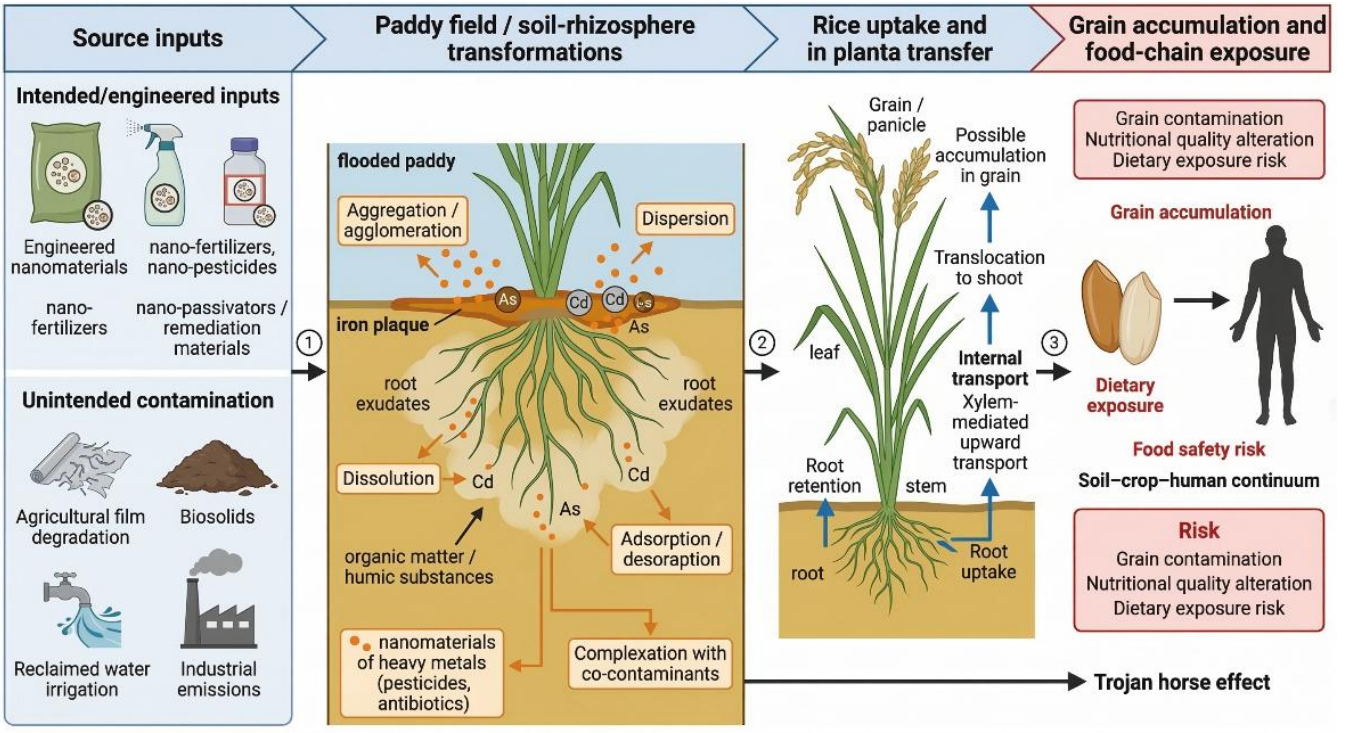


**Fig. 1.** Conceptual overview of source inputs, environmental transformations, plant uptake, and food-chain transfer of nanoparticles (NPs) and micro/nanoplastics (MNPs) in paddy rice systems.

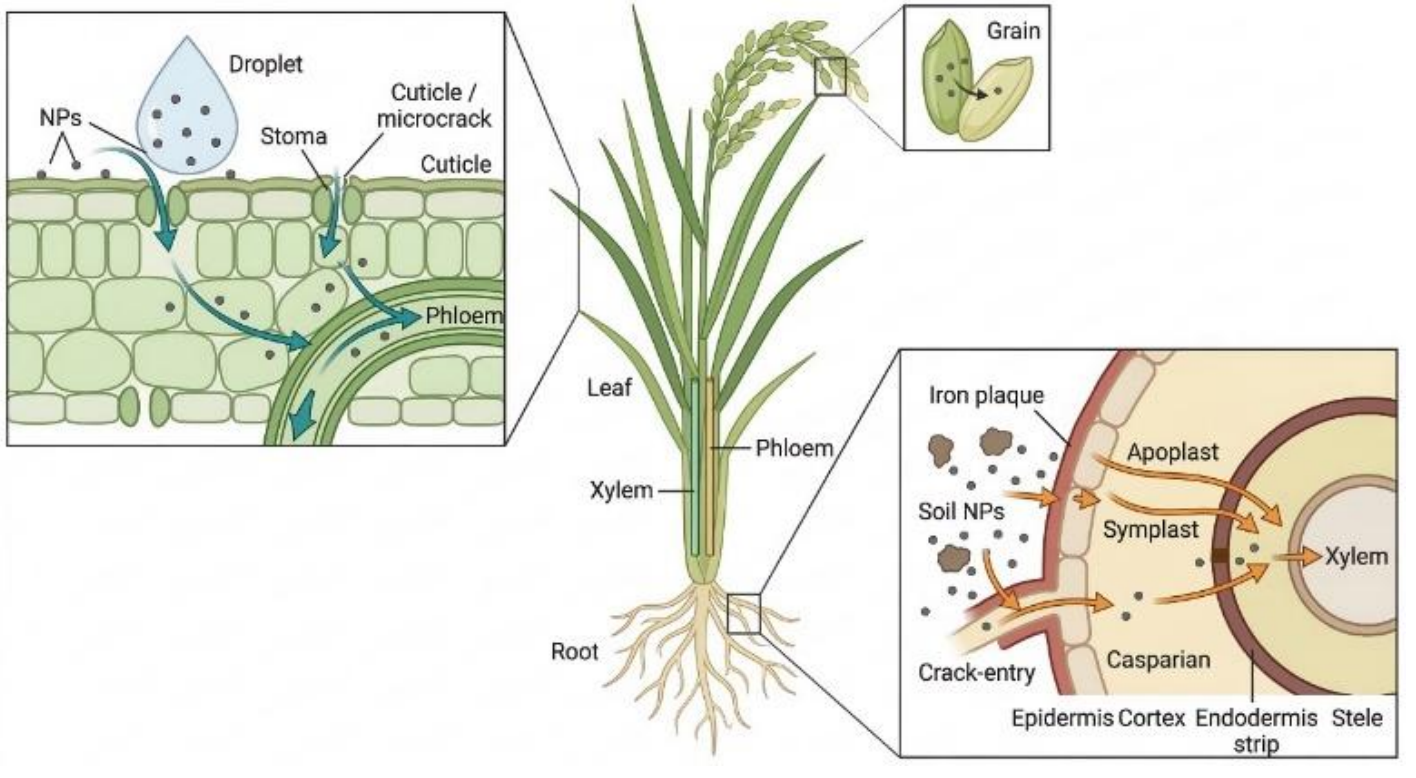


**Fig. 2.** Schematic mechanism of NP uptake and translocation pathways in rice.

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### 2.1. Foliar Uptake and the "Top-Down" Translocation Pathway

The ingress of NPs through foliar surfaces, typically resulting from atmospheric deposition or foliar spraying of nano-formulations, fundamentally involves adsorption, wetting, retention, and penetration at the leaf epidermal interface. The surface waxy layer and cuticle function as the primary defensive barrier, while stomata, polar cuticular pathways, and microscopic surface fissures are recognized as critical potential conduits for NP entry into leaf tissues. Given that stomatal apertures significantly exceed the dimensions of most NPs, they are frequently considered a major entry portal; however, their actual contribution is modulated by plant species, leaf abaxial/adaxial structural discrepancies, droplet surface tension, and ambient humidity [4, 12, 13]. Upon permeating the mesophyll tissue, the subsequent capacity of NPs to cross cellular-level barriers is primarily governed by the size exclusion effect of the cell wall. The average pore size of plant cell walls ranges approximately between 2 and 20 nm, dictating an exclusion threshold generally below 10 nm. Consequently, ultra-small particles readily traverse cell wall pores to enter the apoplastic space, whereas larger particles necessitate endocytosis, induced cell wall remodeling, or exploitation of localized structural defects for internalization [4, 12]. During transmembrane transport in planta, clathrin-mediated endocytosis is relatively well-documented, though alternative non-classical endocytotic pathways may also operate; intracellular particles may further utilize plasmodesmata for symplastic diffusion between adjacent cells, thereby enhancing their localized and systemic mobility.

Regarding the feasibility of substantial phloem loading and subsequent "top-down" transport post-foliar application, an increasing body of evidence supports this occurrence, although its efficacy is heavily contingent upon particle design and plant physiological status. Recent reviews suggest that specific foliarly applied nanoparticles can undergo source-to-sink redistribution toward stems, roots, and newly developing tissues, yet the outcomes reported across various studies exhibit considerable heterogeneity. Therefore, while foliar uptake represents a viable systemic pathway, the below-ground root system remains the predominant and most complex interface for environmental NP interactions in paddy ecosystems [11, 13].

### 2.2. Root Uptake and the "Bottom-Up" Translocation Mechanism

Relative to foliar pathways, the root system is unequivocally identified as the primary point of entry for environmental NPs, particularly metallic nanomaterials and micro/nanoplastics in soil, into the plant interior. As illustrated in Figure 3, prior to penetrating the root epidermis, NPs are subjected to rice-specific rhizosphere features. Iron plaque formation and root exudate secretion play a pivotal role in modulating NP/MNP behavior at this critical interface. These factors collectively regulate particle aggregation, dissolution, adsorption, and complexation with co-contaminants, ultimately determining the particles' retention at the root surface and their potential uptake into the plant.

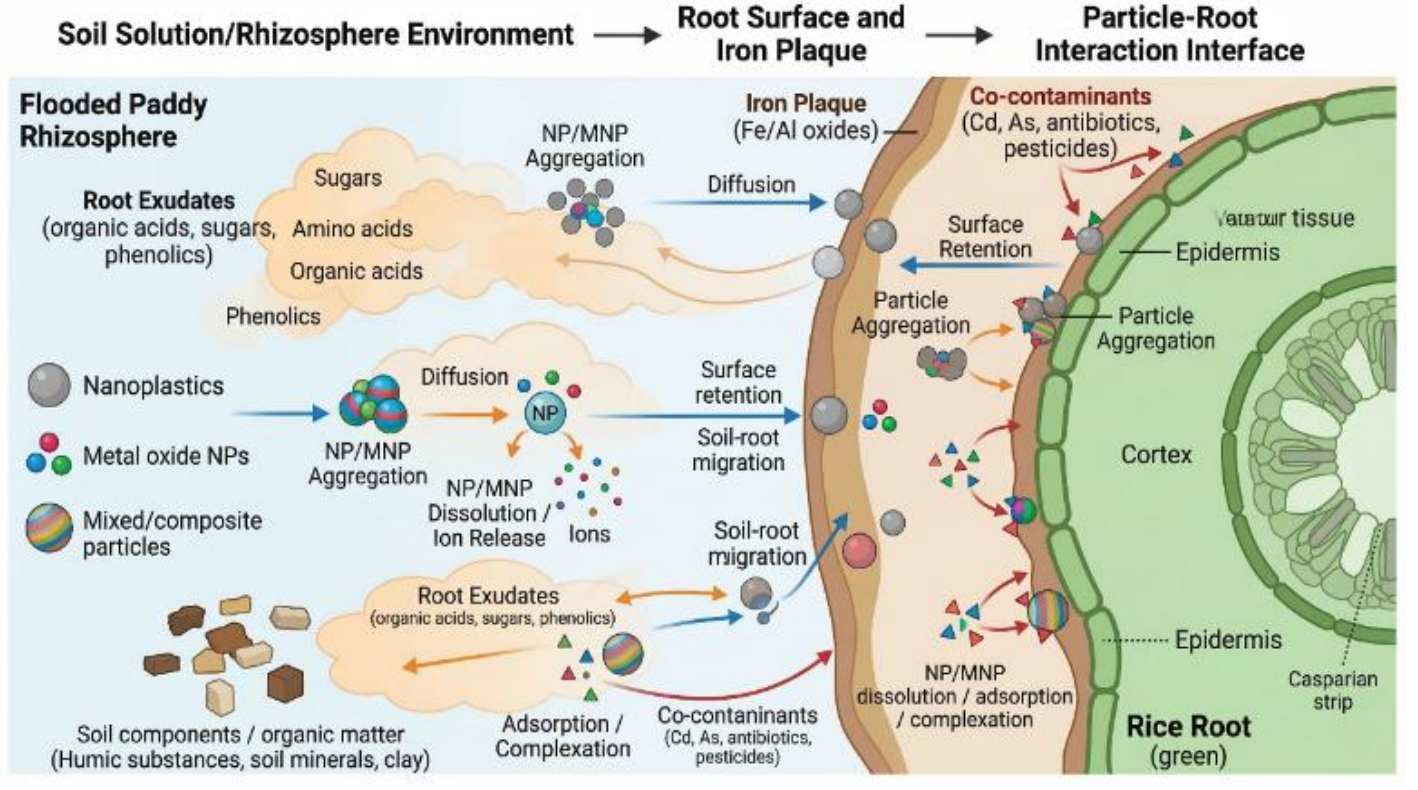


**Fig. 3.** Rice-specific rhizosphere interfacial regulation of nanoparticles (NPs) and micro/nanoplastics (MNPs).


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Following this initial rhizosphere interaction, the transit of NPs from the root epidermis through the cortex to the stele, and their subsequent loading into the xylem, demands the sequential circumvention of the root mucilage layer, cell walls, plasma membranes, and the endodermal barrier. Consequently, their migration behavior is constrained not only by NP properties but is also profoundly influenced by the rhizosphere environment and root tissue developmental stage [4, 12].

Initially, the rhizosphere microenvironment dictates the initial fate of NPs at the root surface. Low-molecular-weight organic acids, amino acids, and mucilage secreted by roots can modify particle surface potential, dispersibility, agglomeration status, and dissolution kinetics, thereby influencing their adhesion to the root surface and subsequent uptake. Root exudates can simultaneously facilitate the dissolution of certain metal-based nanomaterials or induce particle aggregation and alter surface ligand stability, implying that the bioavailability of identical NPs may diverge starkly across different rhizosphere chemical milieus [4].

During transit across the epidermis and cortex, apoplastic and symplastic transport are recognized as the two fundamental modalities. Particles of sufficiently small size, or those capable of inducing cell wall loosening, can migrate through the apoplast along cell walls and intercellular spaces; upon effective interaction with the plasma membrane, they may also transition into the symplastic pathway via endocytosis. The prevailing "cell wall pore size of 5-20 nm" paradigm is insufficient to rationalize all experimental observations, as multiple studies have detected plastic particles significantly exceeding this dimensional threshold within internal root tissues and proximal to vascular bundles, indicating the existence of alternative bypass mechanisms [4, 10, 14].

Recently, the "crack-entry mode" has emerged as a pivotal mechanism elucidating the traversal of larger particles across external root barriers. Structural discontinuities generated during lateral root emergence permit submicron or micron-sized plastic particles to bypass conventional cell wall size restrictions and directly access vascular regions; the formation of "pores/cracks" between root cap protective layers or epidermal cells may offer supplementary conduits for internal root entry. This mechanism is currently best documented for micro/nanoplastics, and its universal applicability to other nanomaterial types warrants further empirical validation [14, 15].

Upon reaching the endodermis, the Casparian strip and associated suberin depositions markedly restrict continuous apoplastic pathways, serving as the critical inner barrier in "bottom-up" root translocation. To penetrate the stele and achieve xylem loading, particles must generally traverse the membrane into the symplast or pass through regions where the endodermis remains incompletely developed. The formation of the Casparian strip is fundamentally an essential structural adaptation restricting apoplastic diffusion of water and solutes, which elucidates why the cross-endodermal transport of NPs is highly contingent upon particle size, surface properties, and root developmental stages [4, 16].

Surface charge frequently governs particle adsorption at the root epidermis and inward migration. Given that plant cell walls are replete with negatively charged groups such as pectin, positively charged particles are generally more prone to electrostatic adsorption at the root surface, often inciting localized membrane damage and oxidative stress; conversely, negatively charged or neutral particles exhibit superior internal migration capacities in specific systems. In rice, polystyrene nanoplastics with distinct functional group modifications display markedly divergent toxicities and transport behaviors; PS-$NH_2$ frequently provokes more intense growth inhibition and oxidative damage, whereas PS-COOH behaves divergently. This pattern remains material- and environment-dependent, rendering it more accurate to state that surface charge significantly impacts root surface retention, transmembrane uptake, and in planta distribution patterns [17, 18].

Following successful traversal of the endodermis and entry into the xylem, NPs can be transported upwards towards the shoots via transpiration pull. For staple crops like rice, the pressing concern is the potential for these particles to reach edible tissues. Polystyrene nanoplastics can enter rice via roots and translocate to grains during late developmental stages, concomitantly decreasing the seed-setting rate, increasing the empty-spikelet rate, and altering nutritional quality. Therefore, post-uptake "bottom-up" migration constitutes not only an issue of phytotoxicology but also poses direct food safety risks [7, 19].

As illustrated in Figure 4, nanoparticles and micro/nanoplastics can enter rice roots via multiple pathways, including apoplastic diffusion, symplastic transport through plasmodesmata, endocytosis, and crack-entry. The endodermal Casparian strip acts as a selective barrier, allowing only particles of certain size and surface properties to reach the pericycle and subsequently be loaded into the xylem for upward translocation. Co-contaminants adsorbed onto NP surfaces may be co-transported, forming a “Trojan horse” effect that facilitates systemic distribution.

### 2.3. Key Physicochemical and Biological Factors Influencing Uptake and Translocation

The efficiency of NP uptake and translocation in planta is not immutable but is the amalgamated outcome of intrinsic plant biological traits and NP physicochemical properties. Plant species, rhizosphere microenvironments, particle sizes, surface charges, and coating chemistries synergistically dictate NP adsorption, transmembrane internalization, internal migration, and ultimate accumulation loci. A systematic deconstruction of these determinants facilitates the ecological risk assessment of emerging contaminants like micro/nanoplastics and provides theoretical grounding for the rational design of high-efficiency, low-risk nano-agrochemicals [4, 10, 20].

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*2.3.1. Plant Species and Rhizosphere Microenvironment Characteristics*

Divergences in plant species function as pivotal initial variables dictating NP uptake modalities. Variations in root architecture, root mucilage, cell wall composition, transpiration intensity, and rhizosphere metabolic activity across species necessitate that, even under identical exposure parameters, the uptake, retention, and upward translocation behaviors of NPs may diverge profoundly. Comparative analyses indicate disparities between monocots and dicots regarding micro/nanoplastic uptake and distribution; however, this cannot be simplistically categorized as universally higher or lower, but rather must be interpreted as the combined effect of plant anatomy and particle properties [4, 21, 22].

For rice, the specificity of the rhizosphere microenvironment is remarkably critical. Under flooded conditions, rice roots facilitate radial oxygen loss, catalyzing the precipitation of iron-rich oxides at the root interface, termed iron plaque. Recent investigations elucidate that iron plaque is not merely a structural adaptation to flooding but profoundly alters the rhizosphere behavior and phyto-availability of elements like Cd, As, and P via adsorption, co-precipitation, and complexation, thereby modulating the retention and entry probability of NPs and their associated co-contaminants at the root surface [23-26]. Furthermore, iron plaque and humic substances can directly modify the uptake and toxicity of nanoplastics in rice roots, with iron plaque shown to mitigate nanoplastic-induced oxidative damage under defined conditions [25, 26].

Beyond iron plaque, root exudates are critical interfacial regulators governing particle fate. Organic acids, amino acids, sugars, and mucilage expelled by roots perturb rhizosphere pH, ionic strength, and coordination environments, thereby provoking nanomaterial aggregation, dispersion, dissolution, or surface transformation. Root exudates can accelerate the dissolution of specific metallic nanomaterials or induce agglomeration in others; generally, agglomeration suppresses plant assimilation, whereas dissolution elevates the bioavailability of elemental species. Thus, the stress-induced augmentation of organic acid secretion in rice likely modulates the subsequent uptake pathways of NPs through rhizosphere chemical regulation prior to their actual entry into root tissues [4, 20, 27]. To further deconstruct these microscopic biochemical interactions, Figure 5 provides a mechanistic deep-dive into the dynamic interplay between root exudates and the iron plaque at the root-soil micro-interface. Building upon the macroscopic pathways depicted earlier, this illustration specifically emphasizes how targeted exudates, such as organic acids and mucilage, chemically modify NP surfaces, driving stabilization, ligand exchange, or co-contaminant hitchhiking within the Fe/Al oxide matrix.

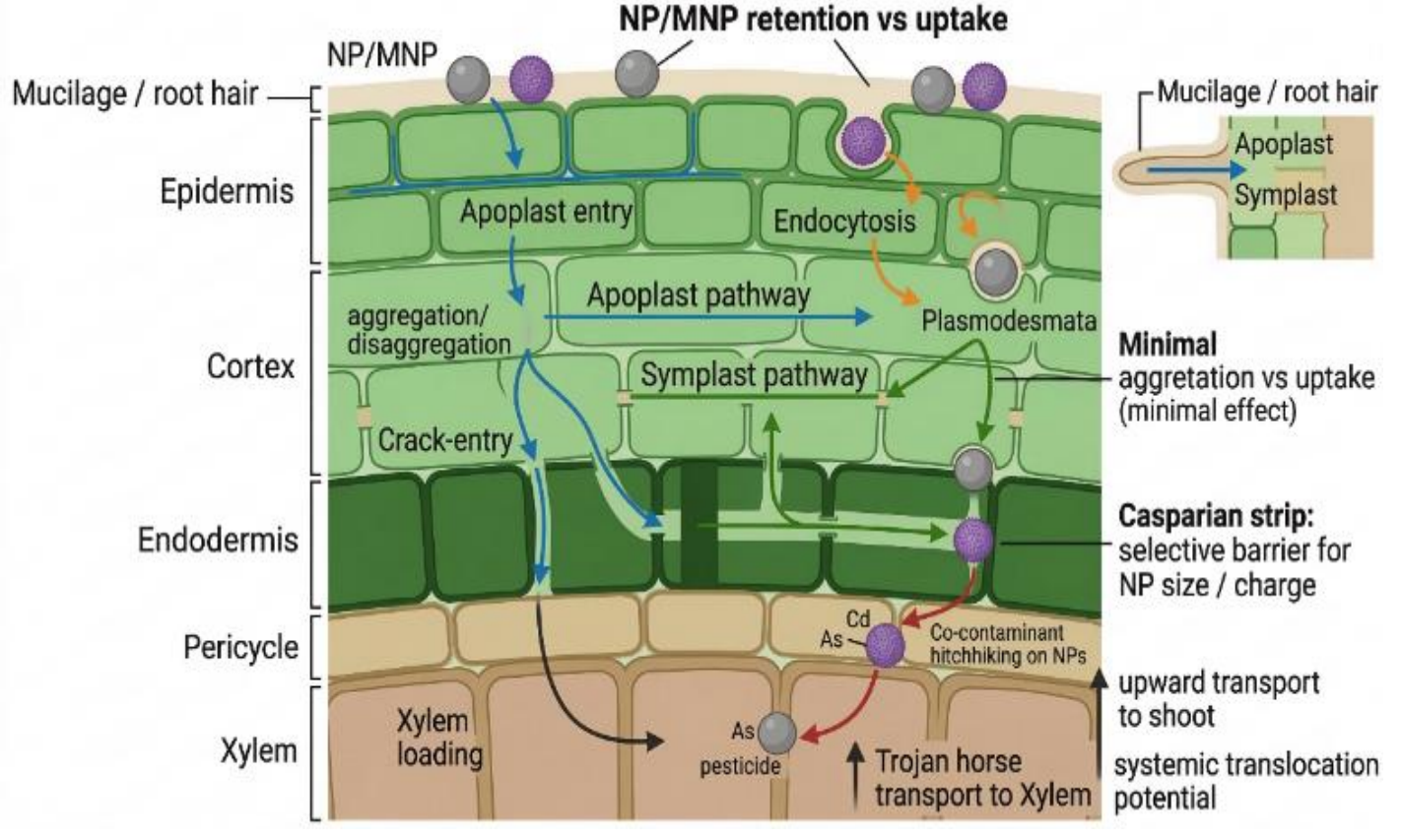


**Fig. 4.** Cellular and tissue-level uptake and translocation pathways of nanoparticles (NPs) and micro/nanoplastics (MNPs) in rice roots.


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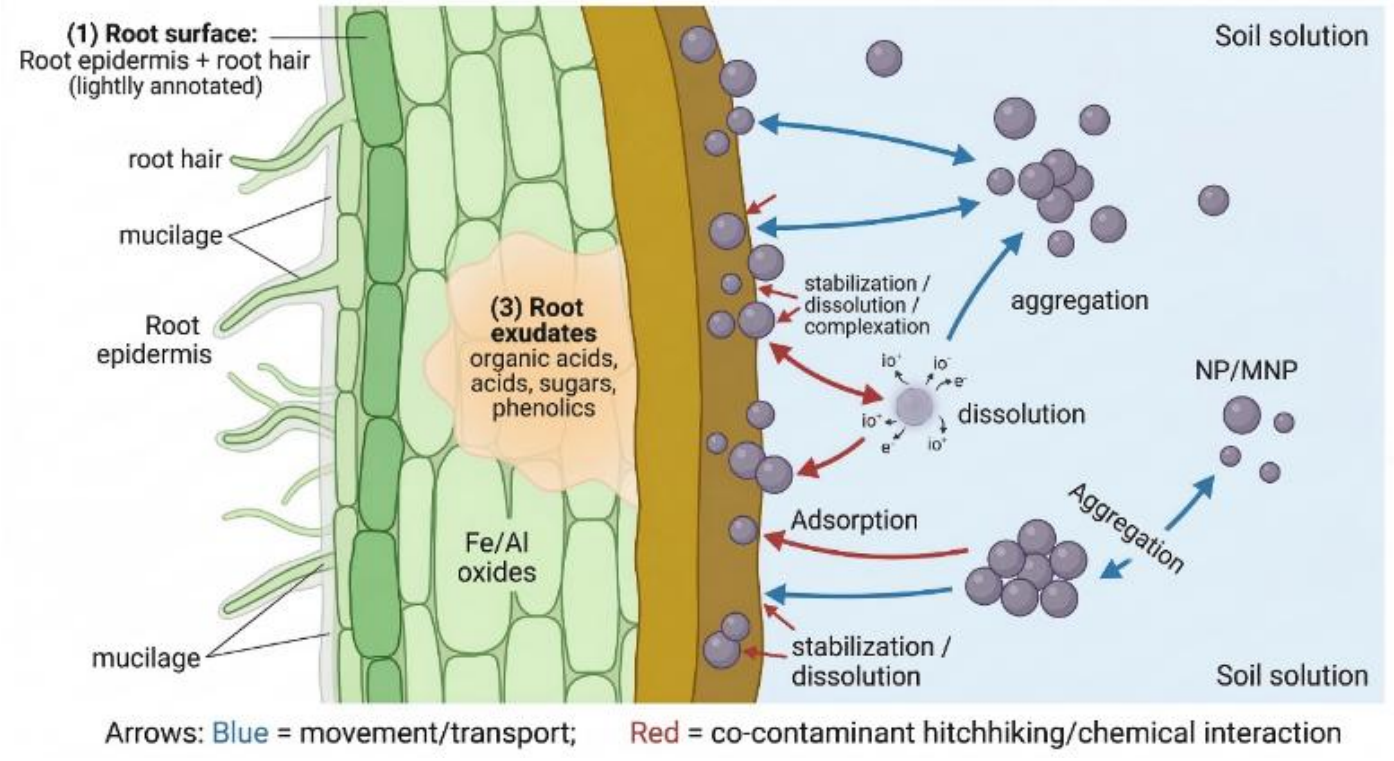


**Fig. 5.** Mechanistic illustration of iron plaque formation and root exudate-mediated nanoparticle interactions in the rice rhizosphere.

### *2.3.2. NP Size and Size Exclusion*

Particle size remains an absolute physical parameter dictating the capacity of NPs to breach plant physiological barriers. The dimensional constraints imposed by cell walls, plasmodesmata, and membrane transport infrastructures mandate that smaller particles generally achieve root surface internalization and internal migration with greater efficacy. The pore size of plant cell walls typically ranges from 2-20 nm, implying that ultra-small particles seamlessly transit through these voids, whereas larger entities are increasingly reliant upon endocytosis, cell wall remodeling, or structural defects as alternative transit routes [4, 10, 20].

Empirical evidence extensively substantiates the size-dependency of NP uptake. In rice, polystyrene particles of varying dimensions and charges elicit distinct discrepancies in root retention, internal migration, and phytotoxicity; exposure to 80 nm, 200 nm, and 2 μm particles precipitated divergent growth inhibitions and physiological responses, demonstrating that scale transitions from nano to micro are sufficient to alter exposure outcomes [17, 28]. While reduced particle size typically correlates with heightened barrier-crossing competence and systemic migration potential, this paradigm is non-absolute, being co-modulated by surface modifications, the exposure matrix, and tissue states [10, 22].

"Size exclusion" does not imply the absolute preclusion of large particles. The "crack-entry mode" suggests that lateral root emergence and epidermal ruptures furnish bypass channels for submicron and micron-sized particles. More accurately, while smaller particles readily achieve systemic translocation, larger particles, though prone to root surface retention, may still ingress into internal tissues given specific structural windows [4, 10].

### *2.3.3. Surface Charge and Coating Chemistry*

The surface charge and chemistry of NPs dictate their initial mode of interaction with the root epidermis. Due to the abundance of negatively charged pectin and carboxyl groups within cell walls and mucilage, positively charged particles are predisposed to intense electrostatic adsorption at the root surface, whereas negatively charged or near-neutral counterparts often exhibit distinct dispersibility and a higher propensity for internal migration in certain matrices. This dynamic, however, manifests pronounced material and environmental dependencies; thus, surface charge fundamentally regulates root surface retention, transmembrane internalization efficiency, and the ensuing in planta distribution topology [4, 17].

In rice, functionalized polystyrene nanoplastics provide direct evidentiary support. PS, PS-COOH, and PS-$NH_2$ exert markedly divergent impacts on rice ontogeny, chlorophyll content, antioxidant systems, and transcriptional/metabolic responses, with amine-modified particles typically inducing more profound biological perturbations and toxicological

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effects. This underscores that surface functionalization alters not only electrostatics but simultaneously modifies interactions with membrane systems, cell walls, and redox homeostasis [17].

Coating chemistry further governs particle stability, agglomeration kinetics, and dissolution profiles within the rhizosphere. Root exudates can induce surface ligand exchange, aggregation, or dissolution, thereby reconfiguring the "authentic particle morphology" accessible to the plant [4]. For metallic or metal oxide nanomaterials, small-molecule ligands and polymer coatings frequently predicate divergent rhizosphere transformation pathways, subsequently modulating uptake efficiencies and biological ramifications. By manipulating the hydrophilicity, coordination capacity, and colloidal stability of coatings, it is feasible to significantly intervene in the rhizosphere transformation and ultimate assimilative fate of NPs [4, 20]. In summary, the uptake and translocation of NPs in rice are governed not by isolated variables, but by the complex interplay of plant biological attributes and particle physicochemical properties. Table 1 enumerates these primary determinants and their mechanistic characteristics.

The key determinants summarized in Table 1 can be further visualized in a conceptual flow map, highlighting how nanoparticle properties, root characteristics, and environmental factors collectively influence retention, translocation, and phytotoxicity in rice (Figure 6). This figure emphasizes the multivariate nature of NP interactions with rice, where a single factor can influence multiple mechanistic pathways, ultimately affecting uptake, systemic distribution, and plant health outcomes. Beyond uptake, various NPs manifest pronounced disparities in biological effects upon entering the rice system. These effects are not merely bifurcated into absolute toxicity or growth promotion, but are co-regulated by material classification, surface properties, exposure dosage, and the rhizosphere milieu. Table 2 summarizes these primary effects and underlying mechanisms

**Table 1.** Primary Factors Influencing NP Uptake and Translocation in Rice.

| Factor | Key Characteristics | Mechanistic Role | Impact on Uptake and Translocation |
|---|---|---|---|
| **Plant Species & Root Traits** | Root architecture, mucilage layer, cell wall composition, transpiration intensity. | Determines adsorption strength at the root surface, barrier penetrability, and internal transport efficiency. | Elicits inter-species or inter-varietal discrepancies in NP uptake, retention, and upward transport capabilities. |
| **Rhizosphere Microenvironment** | Iron plaque, root exudates, pH, redox conditions, organic matter. | Regulates particle aggregation, dispersion, complexation, dissolution, and surface transformations. | Can either impede NP entry or enhance their bioavailability. |
| **Particle Size** | Ultra-small NPs, standard NPs, micron-sized particles. | Governs transmembrane transport via cell walls, endocytosis, and crack-entry dynamics. | Diminished size generally correlates with enhanced barrier penetration and systemic long-distance transport capacity. |
| **Surface Charge** | Positive, negative, or near-neutral. | Modulates electrostatic interactions with cell walls and root surface mucilage. | Positively charged particles frequently accumulate at the root surface, inducing localized toxicity; negative/neutral particles exhibit divergent internal migration behaviors. |
| **Coating Chemistry** | Polymer coatings, small-molecule ligands, carboxyl/amino modifications. | Alters colloidal stability, dissolution kinetics, and membrane interactions. | Influences physicochemical speciation in the rhizosphere and subsequent tissue distribution. |
| **Root Developmental State** | Lateral root formation, root apex structure, epidermal integrity. | Furnishes localized structural discontinuities. | Facilitates the formation of bypass conduits for particulate entry into internal root tissues. |
| **Endodermal Barrier** | Casparian strip, degree of suberization. | Restricts continuous apoplastic transit into the stele. | Constrains xylem loading and subsequent upward translocation efficiency. |


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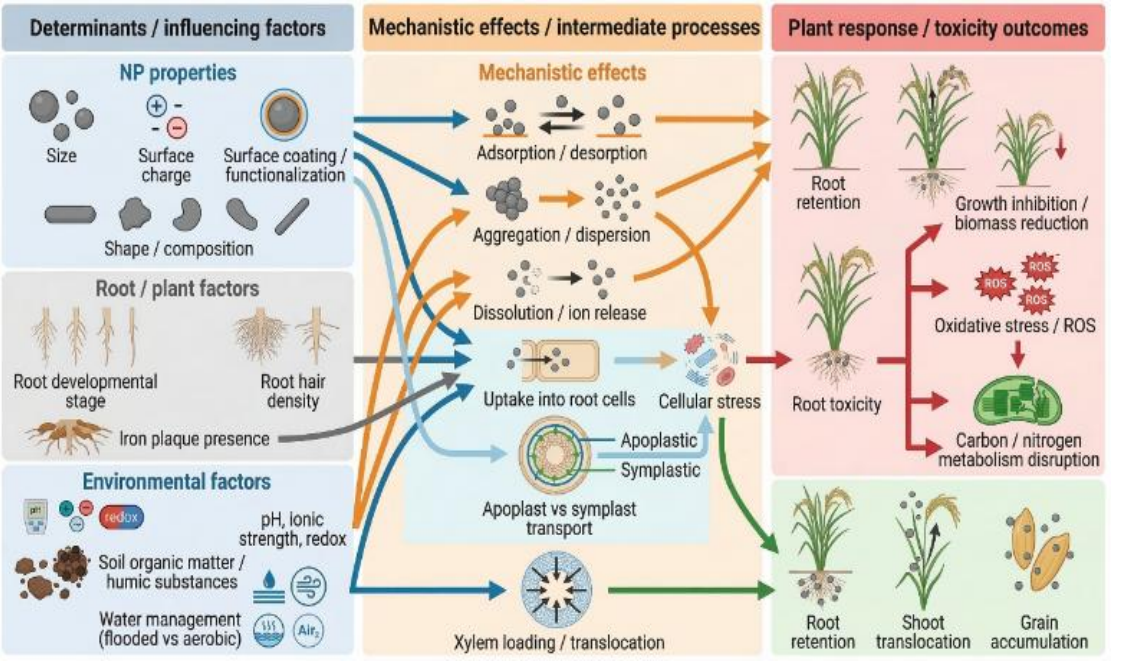


**Fig. 6.** Key determinants controlling nanoparticle (NP) retention, translocation, and phytotoxicity in rice.

**Table 2.** Principal Effects and Mechanisms of Diverse Nanomaterials in Rice.

| Material Category | Representative Materials | Primary Effects | Potential Mechanisms | Comprehensive Evaluation |
|---|---|---|---|---|
| **Nano-Agrochemicals** | Nano-silicon, nZVI, specific nano-fertilizers/pesticides. | Enhances stress tolerance, attenuates Cd and As accumulation, occasionally promotes growth. | Regulates the rhizosphere environment, passivates contaminants, improves nutrient provision, activates antioxidant systems. | Exhibits substantial potential for agricultural application. |
| **Metal/Metal Oxide NPs** | Fe-based, $TiO_2$, ZnO, Cu-based NPs. | Can induce growth promotion or phytotoxicity. | Ion release, redox modulation, membrane disruption, and nutrient interference. | Efficacy and toxicity are strictly governed by dosage and surface characteristics. |
| **Nanoplastics** | PS, PS-COOH, PS-$NH_2$, etc. | Inhibits growth, induces severe oxidative stress, disrupts metabolic pathways. | Interacts with cell walls/membranes, triggers ROS accumulation, impedes systemic transport. | Constitutes a primary contemporary environmental risk. |
| **Microplastics and Larger Particles** | Submicron to micron-sized plastic particles. | Root surface retention, pore occlusion, growth suppression. | Physical obstruction, rhizosphere perturbation, and crack-entry dynamics. | Systemic translocation is constrained, yet ecological risks persist. |
| **Co-contaminant Vector Particles** | NPs adsorbing Cd, As, pesticides, antibiotics. | Modifies co-contaminant bioavailability and *in planta* distribution. | Adsorption/desorption kinetics, complexation transformations, and "Trojan horse" dynamics. | Necessitates stringent monitoring of combined pollution risks. |
| **Rhizosphere Interface-Regulated NPs** | NPs interacting with iron plaque, humic substances, and root exudates. | Toxicity and mobility profiles can be either amplified or mitigated. | Rhizosphere adsorption, complexation, and aggregation/dispersion transformations | Exemplifies the intricate interfacial regulatory characteristics inherent to rice agroecosystems. |

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Nanoparticle and micro/nanoplastic exposure triggers a cascade of physiological and metabolic responses in rice, starting with reactive oxygen species (ROS) burst and activation of antioxidant defense systems (Figure 7). Subsequent effects include membrane lipid peroxidation, photosystem impairment, and disruption of carbon and nitrogen metabolism, ultimately leading to growth inhibition and yield or grain quality reduction. Co-contaminants associated with particles may exacerbate these responses via a "Trojan horse" mechanism.

In addition to uptake and translocation behaviors, NPs elicit a pronounced dual biological effect upon integration into the rice system. As conceptualized in Figure 8, this "double-edged sword effect" necessitates a nuanced evaluation of their potential agricultural utility versus environmental risk. On the beneficial edge, rationally designed nano-agrochemicals, such as nano-silicon or nanoscale zero-valent iron (nZVI), can function as elicitors to activate plant antioxidant defenses and effectively immobilize heavy metals like Cd and As in the rhizosphere, thereby mitigating their toxicity and grain accumulation. Conversely, on the hazardous edge, emerging contaminants like micro/nanoplastics, or improperly dosed metallic NPs, provoke severe oxidative stress (ROS burst), impair photosynthetic apparatuses, and disrupt essential carbon-nitrogen metabolic pathways. Consequently, the trajectory of NP impact is not absolute but highly context-dependent, ultimately dictated by the complex interplay of particle properties, such as size, charge, coating, exposure dosage, rhizosphere redox conditions, and crop phenological stages. Beyond direct phytotoxicity, the high specific surface area and reactivity of NPs and micro/nanoplastics transform them into potent vectors within complex, multi-contaminated paddy environments. As depicted in Figure 9, these particles can strongly adsorb organic and inorganic co-contaminants, including heavy metals, for instance, Cd, As, pesticides, and antibiotics. This complexation fundamentally alters the bioavailability and mobility of the hitchhiking pollutants. By bypassing traditional root exclusion barriers via the aforementioned 'crack-entry' or endocytotic pathways, the particle-contaminant complexes facilitate enhanced root-to-shoot translocation and eventual accumulation in edible rice grains. This insidious "Trojan horse" mechanism not only exacerbates systemic plant stress but also poses profound food safety risks by amplifying dietary exposure along the soil-crop-human continuum. Therefore, evaluating these co-contaminant vectoring dynamics is paramount for comprehensive agricultural risk assessment and management strategies.

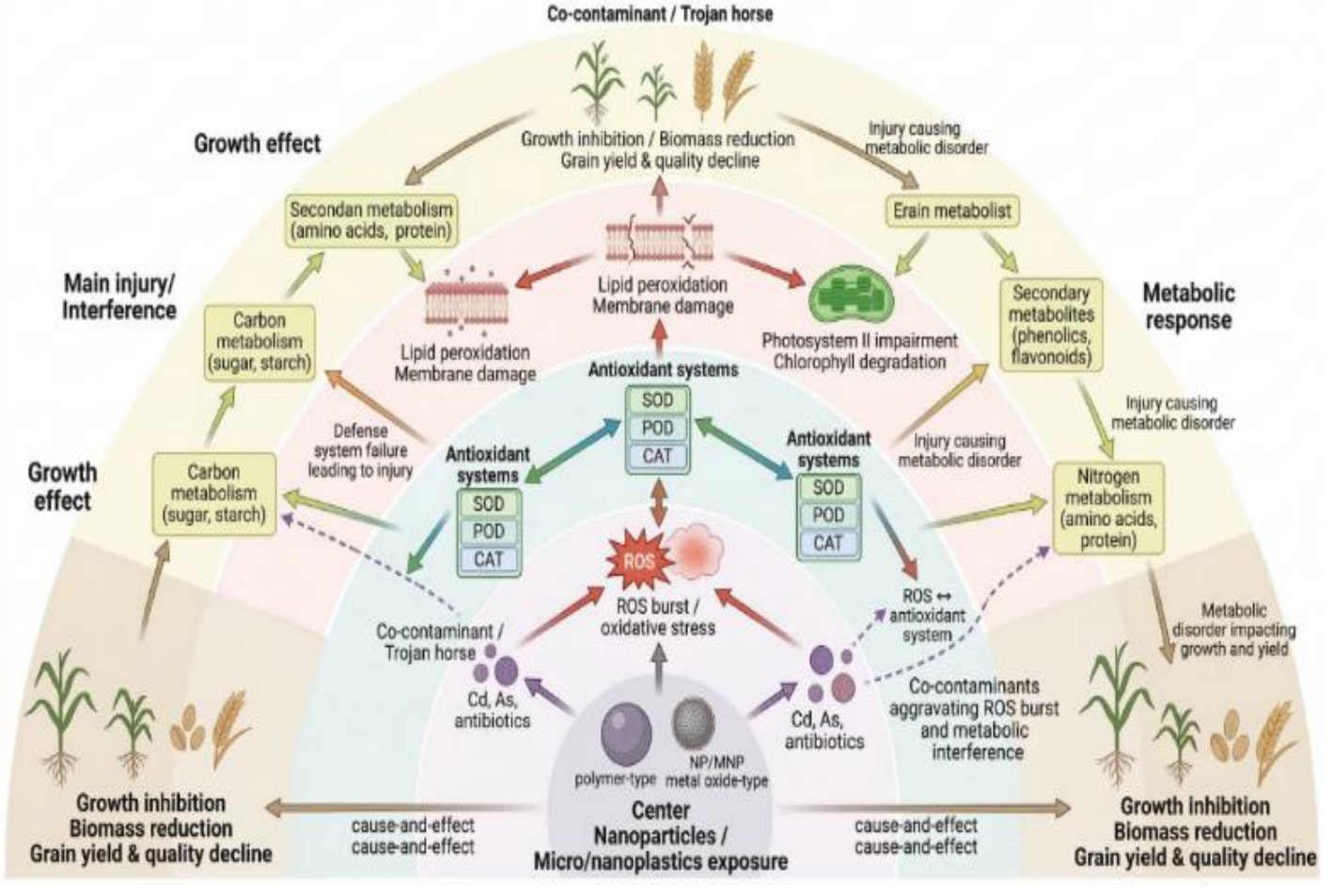


**Fig. 7.** Physiological and metabolic response network of rice exposed to nanoparticles (NPs) and micro/nanoplastics (MNPs).

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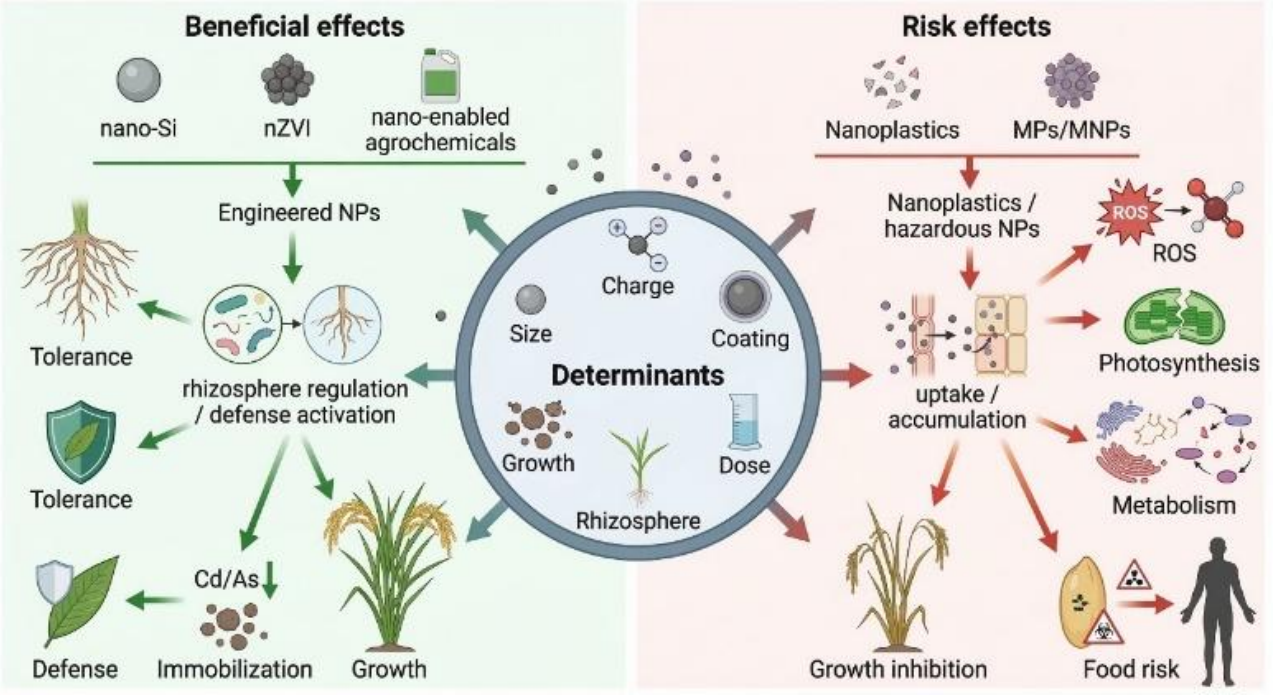


**Fig. 8.** Schematic of the "double-edged sword effect" of NPs on rice and potential mechanisms.

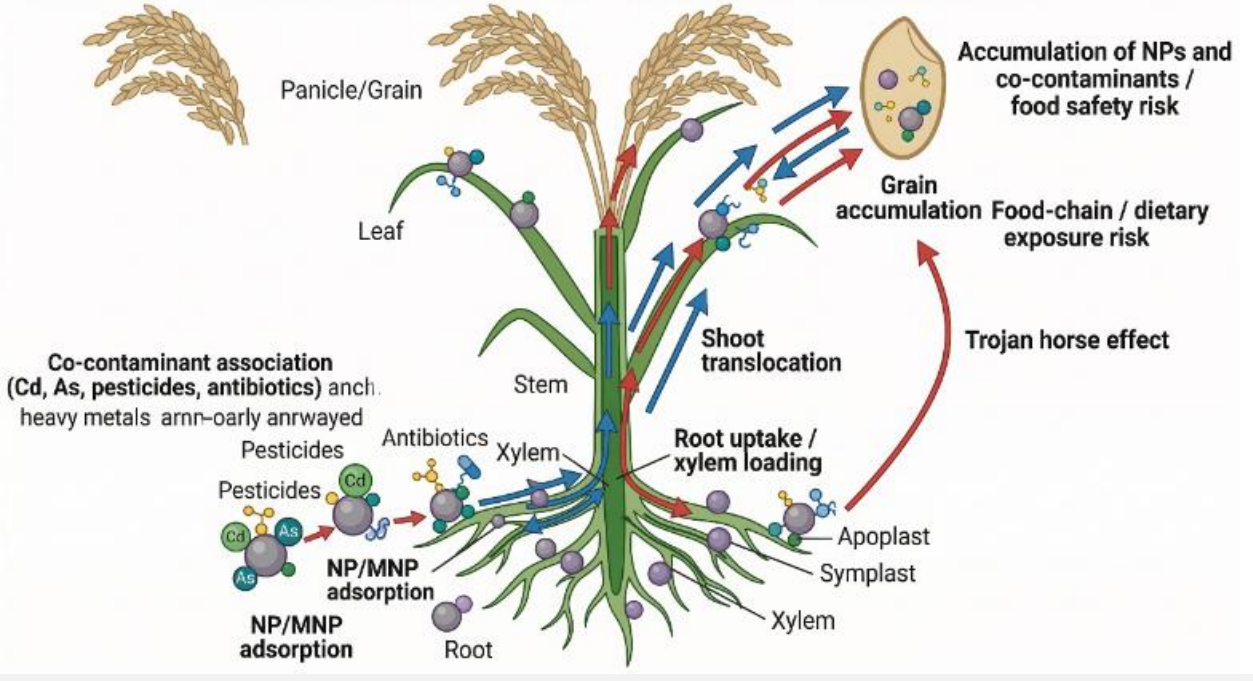


**Fig. 9.** Trojan-horse transport of co-contaminants by nanoparticles (NPs) and micro/nanoplastics (MNPs) and implications for rice grain safety.

## 3. CONCLUSION

The behavior and subsequent effects of NPs within rice agroecosystems are demonstrably dualistic and context-dependent. Drawing upon the established uptake mechanisms, controlling factors, and biological consequences, this review posits several conclusions and outlines trajectories for future inquiry.

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The interplay between NPs and rice roots is a dynamic continuum encompassing interfacial adsorption, rhizosphere transformation, tissue barrier penetration, and systemic redistribution. The rice rhizosphere, particularly the root iron plaque, exudates, and anatomical barriers, profoundly modulates the retention, uptake, and acropetal transport of NPs and their associated contaminants. Concurrently, the ultimate fate of NPs is rigidly dictated by their particle size, surface charge, coating modifications, and colloidal stability, leading to substantial variations in internal migration and accumulation loci across different particle types. Generally, smaller particles possessing enhanced mobility and surface characteristics conducive to transmembrane interactions are more prone to systemic root-to-shoot translocation, whereas highly adsorptive particles typically induce localized root toxicity [23, 29].

Biologically, NPs exert a pronounced “double-edged sword” effect on rice. Certain nano-agrochemicals can remediate rhizosphere conditions, augment antioxidant defenses, and suppress the translocation of toxic elements like Cd and As into edible tissues, thereby demonstrating potential for growth promotion and pollution mitigation. Conversely, emerging nano-pollutants such as micro/nanoplastics incite root oxidative stress, metabolic disruption, and growth suppression; these contaminants may additionally alter physiological homeostasis and elevate food safety risks by perturbing root iron plaque, humic interfaces, and vascular transport pathways [30, 31].

Consequently, the environmental and agricultural impacts of NPs in rice systems defy simplistic binary categorization as exclusively "beneficial" or "detrimental." Rather, their behavior manifests as a highly dynamic continuum, synergistically governed by particle physicochemical attributes, exposure stoichiometry, unique paddy-soil redox fluctuations, and crop ontogeny. Establishing an integrative investigative framework, spanning from "rhizosphere interactions and in planta translocation" to "phytotoxicity and dietary risk", is paramount. Such a holistic paradigm is foundational for uncoupling the sustainable agricultural utility of engineered nanomaterials from the environmental safety thresholds of emerging nano-pollutants, ultimately guiding precise nano-enabled agricultural interventions [10, 32].

## 4. CURRENT LIMITATIONS AND FUTURE PERSPECTIVES

Despite the exponential proliferation of studies regarding NP behavior and impacts in rice ecosystems, critical bottlenecks persist.

Primarily, a significant proportion of contemporary research relies on hydroponics, pot experiments, and disproportionately high exposure dosages, creating a substantial incongruity with authentic paddy field environments. Recent reviews consistently caution that uptake and toxicological paradigms derived from simplified laboratory settings may not seamlessly extrapolate to genuine paddy systems, which are characterized by complex mineral phases, organic matter interactions, redox fluctuations, and chronic, low-dose exposures. Future endeavors must prioritize field or semi-field trials utilizing environmentally relevant concentrations across the complete phenological cycle to rigorously evaluate the chronic accumulation kinetics of NPs and their genuine impact on yield and quality metrics [3, 10, 33].

Secondly, the multidimensional "soil-rice-microbiome" interaction mechanisms remain inadequately elucidated. While the rice rhizosphere microbiome is intimately linked to the activation, passivation, and phytotolerance of contaminants like Cd, systemic evidence detailing how NP exposure reconstructs this micro-ecological network, and how such microbial successions reciprocally modulate NP uptake and plant stress responses, is severely lacking. This necessitates the integration of metagenomics, metabolomics, and advanced rhizosphere chemical profiling to decipher how NPs and rhizosphere microecology collectively dictate plant exposure outcomes [34].

Thirdly, the "Trojan horse" effect within the context of composite pollution represents a pronounced vulnerability in current risk assessments. In agricultural settings, NPs routinely co-exist with heavy metals, pesticides, and antibiotics; furthermore, nanoplastics and specific high-surface-area nanomaterials exhibit formidable adsorptive and vectoring capacities. Risk evaluations must transition from isolated particle toxicity models to complex "NP-co-contaminant-crop" matrices, with a specific focus on elucidating adsorption/desorption kinetics, interfacial transformations, and synergistic/antagonistic effects within the rhizosphere [10].

Fourthly, the in situ identification, morphological characterization, and absolute quantification of NPs in planta encounter formidable technological impediments. Traditional fluorescent tagging is susceptible to desorption, photobleaching, and matrix interference, rendering it insufficient for high-fidelity quantification, particularly concerning nanoplastics and specific carbonaceous nanomaterials. Pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS) is emerging as an indispensable analytical tool for the identification and quantification of micro/nanoplastics and is increasingly being adapted for botanical matrices. Correspondingly, integrative methodologies employing environmentally realistic particles, isotopic or elemental tracing, and high-resolution microscopy are paramount for surmounting current quantitative barriers in plant tissue analysis [35-38].

Ultimately, the assessment of food chain transfer risks and human health implications must transcend qualitative observations of "whether entry into the grain occurs" to achieve quantitative evaluations of "the actual exposure significance post-entry." For globally critical staple crops like rice, future research must formulate rigorous risk assessment frameworks that incorporate dietary exposure models, simulated gastrointestinal digestion (bioaccessibility), and defined toxicological endpoints [10, 32, 33].


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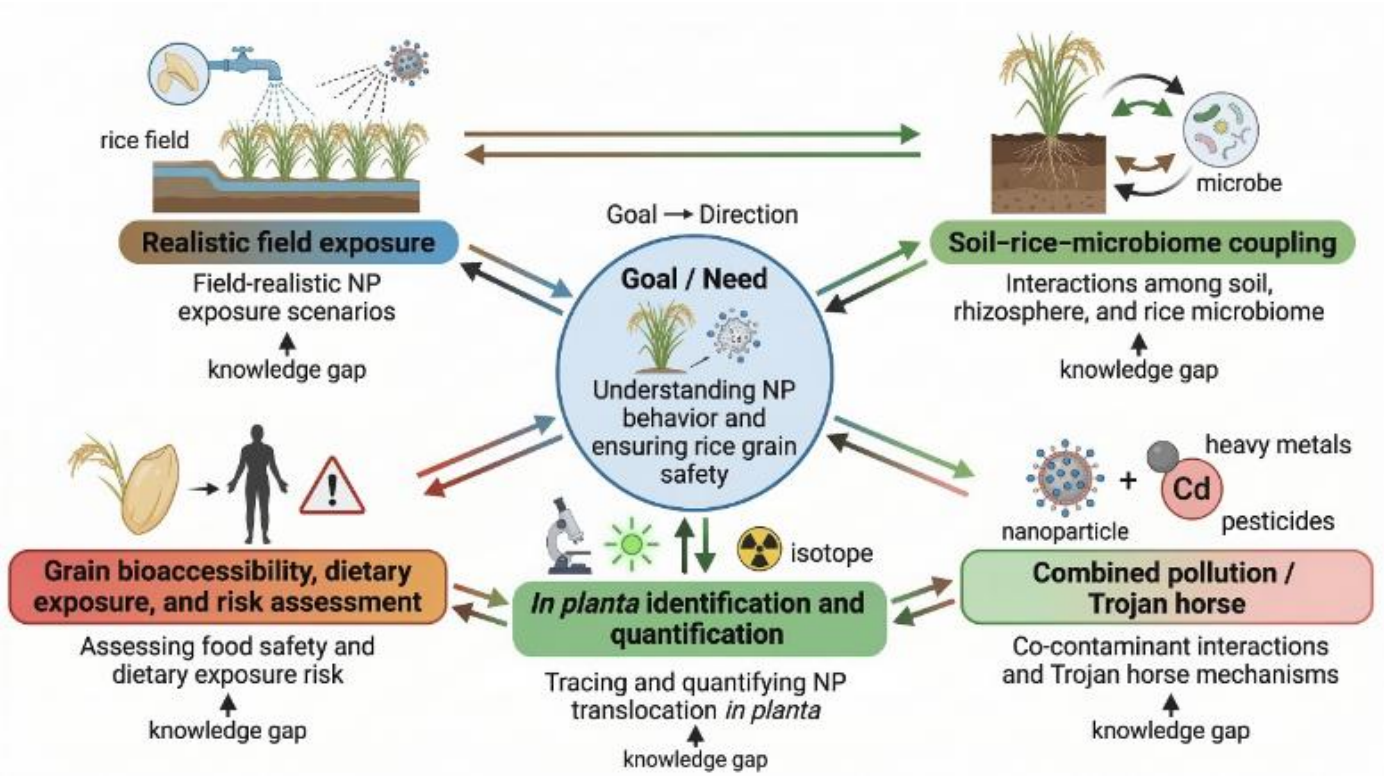


**Fig. 10.** Future research roadmap for nanoparticle (NP) studies in rice agroecosystems.

To systematically dismantle the current knowledge bottlenecks, we propose a comprehensive future research roadmap (Figure 10) anchored in five pivotal directions: (1) realistic field exposure scenarios; (2) soil-rice-microbiome coupling; (3) combined pollution and Trojan horse mechanisms; (4) advanced in planta identification and absolute quantification; and (5) grain bioaccessibility and dietary risk assessment. Navigating these interconnected pathways will provide the definitive scientific substantiation required to formulate robust regulatory frameworks, thereby safeguarding global food security in an increasingly nano-enabled and plastic-polluted era.

## DECLARATIONS

### Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

### Availability of data and material

All of the data obtained or analyzed during this study is included in the report that was submitted.

### Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

### Authors' contributions

All authors contributed equally to this work.

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