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Ecological and physiological risks of micro- and nanoplastics in rice agroecosystems: Challenges and engineering-based mitigation approaches

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ABSTRACT

Micro- and nanoplastics (MNPs) are emerging pollutants that threaten terrestrial agroecosystems, including rice (*Oryza sativa* L.), a key global staple crop. This review synthesizes recent findings on morphological, physiological, and molecular responses of rice to MNPs, and highlights ecological risks to soil fertility and food security. MNPs disrupt root development, reduce biomass accumulation, impair photosynthesis, and alter hormonal and molecular signaling, leading to yield losses under combined stress conditions. At the soil level, MNPs alter microbial communities, reduce nutrient cycling efficiency, and increase heavy metal bioavailability. Despite extensive laboratory studies, real-field evidence remains scarce, and mitigation strategies are underexplored. This paper proposes ecological engineering solutions, including organic amendments, microbial bioremediation, phytoremediation, and climate-smart soil management practices to reduce MNPs accumulation. We emphasize the need for standardized testing protocols, long-term field trials, and multi-omics integration to assess ecological risks. By linking plant physiological responses with engineering-based solutions, this review provides a framework for sustainable management of MNPs contamination in agricultural systems.

Keywords: microplastics, nanoplastics, rice, agroecosystems, ecological engineering, oxidative stress, sustainable agriculture.

INTRODUCTION

Over the past few decades, the increasing production and use of plastics have posed serious environmental challenges. The accumulation of plastic waste, which is resistant to degradation, has resulted in the formation of very small fragments that enter various ecosystem compartments. MNPs, defined as plastic particles measuring less than five millimetres, are widespread environmental pollutants affecting a variety of ecosystems, from aquatic habitats to terrestrial soils (Hasan et al., 2024; Kumar et al., 2025). The global growth in the production and use of synthetic polymers has led to a significant increase in plastic in the environment. Plastics are highly durable and slow to degrade, allowing them to persist for a long time in nature (Choudhury and Roy, 2025). To date, MNPs have been found in almost all layers of the environment, including air, water, and soil (Shirley et al., 2025). In fact, MNPs have been detected in human blood, various organs, and breast milk (Jaikumar et al., 2025). This indicates that MNPs have entered the entire chain of life. In terrestrial environments, MNPs are now considered a serious threat, especially in the context of agricultural sustainability and human health (Yang et al., 2024; He et al., 2024; Li et al., 2024).

MNPs in soil generally originate from the decomposition of large plastic debris and the release of microbeads from personal care products (de

Souza Machado et al., 2018; Goh et al., 2025). In addition, wastewater from water treatment plants also contributes to MNPs entering the ecosystem (Ormaniec and Mikosz, 2024). The most common forms of MNPs in soil are fragments and fibres, with polyethene and polypropylene being the most dominant polymers (Neuburg et al., 2025; Kandaiah et al., 2024). Some of the most frequently found types are polyethene terephthalate (PET) and polyvinyl chloride (PVC) (Dainelli et al., 2023).

The application of compost from municipal solid waste is one of the main routes of MNPs entry into agricultural land. This compost can contain up to 106.7 kg of macroplastics/ha and billions of MNPs particles per hectare in a single application (Neuburg et al., 2025). However, the use of MNPs in research still uses a homogeneous and non-decomposed form, so it does not represent real conditions in the environment (Bitton et al., 2025).

MNPs contamination can cause changes in soil physicochemical properties such as pH, water retention, and nutrient availability, as well as affect the structure of the microbial community and overall soil fertility (Lalrinfela et al., 2024). This condition ultimately inhibits plant growth, reduces yields, and disrupts plant physiological performance. The impact of MNPs on plants has been widely studied, producing findings ranging from stimulating growth and inhibiting growth to having no significant effect (Tunali and Rillig, 2025). However, MP remains a major stressor that can potentially disrupt long-term agricultural productivity.

Given the wide distribution of MNPs and the complexity of their effects on biological systems, a comprehensive review is needed to deeply understand the interaction mechanisms of MNPs on the growth, physiology, and molecular responses of major food crops such as rice. Therefore, this paper aims to summarize and systematically review the current literature on the impacts of MNPs stress on rice plants, covering morphological, physiological, and molecular aspects and providing an overview of challenges and future research directions.

Definition and types of micro- and nanoplastics

Ecological risks also extend to aquatic and air systems, particularly as MNPs can carry other pollutants such as PM2.5, which can exacerbate impacts on human respiratory and cardiovascular health (Wang et al., 2025). Specifically, degraded polyethene has been linked to the death of immune and epithelial cells through necrosis mechanisms (Ikuno et al., 2024). In soil-water systems, the presence of highly reactive free radicals also exacerbates toxicity risks (Zhu et al., 2025).

MNPs pollution can have significant consequences for soil ecosystems, such as reduced plant productivity, disrupted food chains, and even potential groundwater contamination (Bian et al., 2024; Apte et al., 2024). Overall, the presence of MP in the environment has become a real threat that not only affects ecological stability but also has the potential to endanger human health (Pan et al., 2024; Horváth et al., 2025).

MNPs has become a major concern in the past decade as one of the emerging pollutants with widespread impacts on ecosystems, including agricultural systems. Microplastics are generally defined as plastic particles smaller than 5 mm, while nanoplastics are in the range of less than 0.1 µm (Figure 1). Both are the result of the gradual degradation of macro plastic waste that is widely dispersed in the environment (Dehghanian et al.,

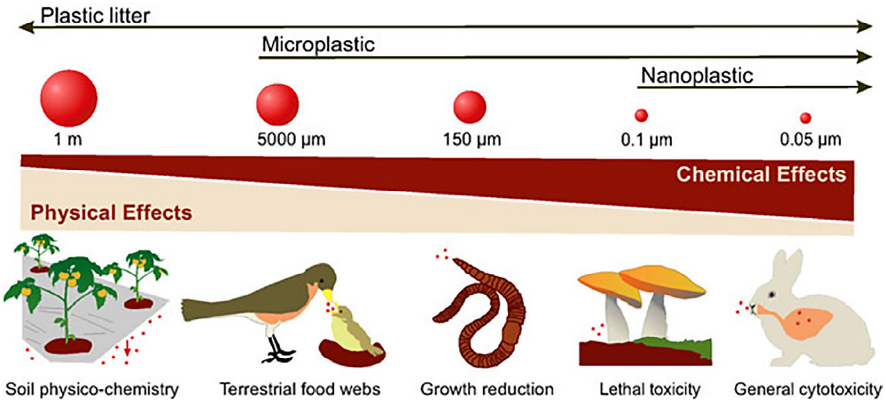

Figure 1. Differences in plastic size (from large plastic to nano), as well as the physical and chemical effects of MNPs on various organisms and the environment (de Souza Machado et al., 2018)

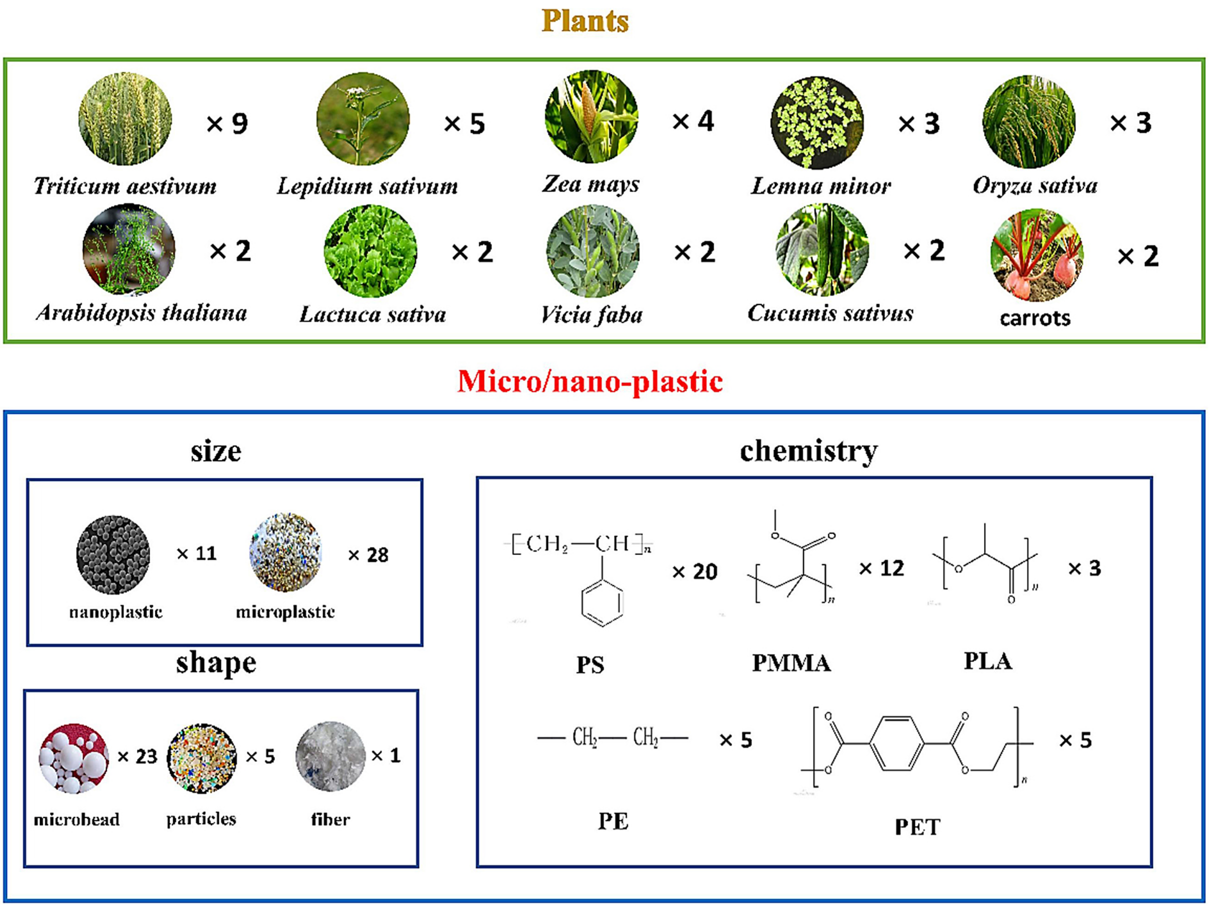

Figure 2. Various types of MNPs (Yu et al., 2024)

2023). This fragmentation process occurs naturally through physical, chemical, and biological influences, but it is prolonged, leading to the accumulation of persistent particles in various environmental media.

The presence of MNPs in agricultural soils, particularly in rice cultivation systems, is a serious and growing challenge. MNPs can enter agricultural land through various pathways, including contaminated irrigation water, application of contaminated organic compost, and inadequate plastic waste management. In the specific context of rice farming, the distribution and accumulation of MNPs are greatly influenced by water movement and the unique redox dynamics of paddy soil (Yustres et al., 2025). The presence of MNPs in the rhizosphere environment can alter the physicochemical characteristics of the soil and interact directly with plant roots.

The particle size of MNPs significantly determines their penetration rate and toxicity within plant tissues. Nano-sized particles have a high surface area-to-volume ratio, enabling them to penetrate plant cell walls more efficiently and potentially cause intracellular damage such as membrane disruption, organelle dysfunction, and oxidative stress (Liese et al., 2024; Yang et al., 2024). However, the specific molecular mechanisms by which particle size influences metabolic pathways and gene expression in plant tissues remain poorly understood.

Chemically, Based on Figure 2 MNPs originate from two main categories of polymers: thermoplastics and thermosets. Thermoplastics such as polyethene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and polyethene terephthalate (PET) are the most commonly found in environmental contamination due to their widespread use in every day.

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Meanwhile, although present in smaller quantities, thermosets such as polyurethane (PU), epoxy resin, and vinyl ester have high stability, making them persistent once released into the environment.

Differences in physical characteristics, such as shape (fragments, films, fibres), colour, and size, also influence the bioavailability and reactivity of MNPs toward living organisms. Small-sized fragments with irregular surfaces exhibit a higher affinity for the adsorption of heavy metals, pesticides, and hazardous organic compounds, thereby increasing the risk of toxicokinetics toward rice plants. A study by Liese et al. (2024) reported that nano-sized particles can enter tissues through cuticle openings or root pores and may undergo translocation to leaves and reproductive organs via transpiration flow. In agricultural ecosystems, the role of MNPs as a new abiotic stressor is becoming increasingly evident. In addition to affecting soil structure and rhizosphere microbial dynamics, their presence also disrupts plant physiology, including nutrient uptake, photosynthesis, and antioxidant activity. Several studies have reported that MNPs accumulation can reduce crop yields, modify root architecture, and stimulate the expression of stress genes (Yang et al., 2024; Lalrinfela et al., 2024). There are four mechanisms (Figure 3), namely, the apoplastic pathway, which includes cell walls and intercellular spaces where water and solutes move without entering the cell cytoplasm. Plastic particles moving through this pathway can bypass some cellular detoxification mechanisms and spread from the root epidermis to the cortex, then through the endodermis to the stele. This allows the particles to reach the vascular tissue. The crack-entry pathway in roots, due to their petite size, allows MNPs to penetrate micro-cracks on the root surface and spread through plant tissue. This can cause blockages within the vascular tissue or disrupt the function of root cells. Endocytosis also serves as a mechanism for MNP entry, where the cell membrane envelops the microplastic particles and forms internal vesicles that transport these particles into the cytoplasm. This process allows microplastics to enter cells and interact with cellular organelles, which can disrupt normal cell function. Finally, MNPs can also damage plants through stomata, openings in the leaf epidermis that regulate gas exchange and transpiration. Nano-plastic particles in the atmosphere or leaf surfaces can enter plant tissues through these stomata. Once inside, these particles can spread into the leaf mesophyll and interact with leaf cells, disrupting the plant's normal physiological functions (Yu et al., 2024).

Morphological response of rice to micro- and nanoplastics

Morphological response of leaves

MNPs are commonly found in agricultural soil, primarily due to anthropogenic activities such as intensive farming, irrigation systems, and plastic waste. Plastic pollution in terrestrial environments

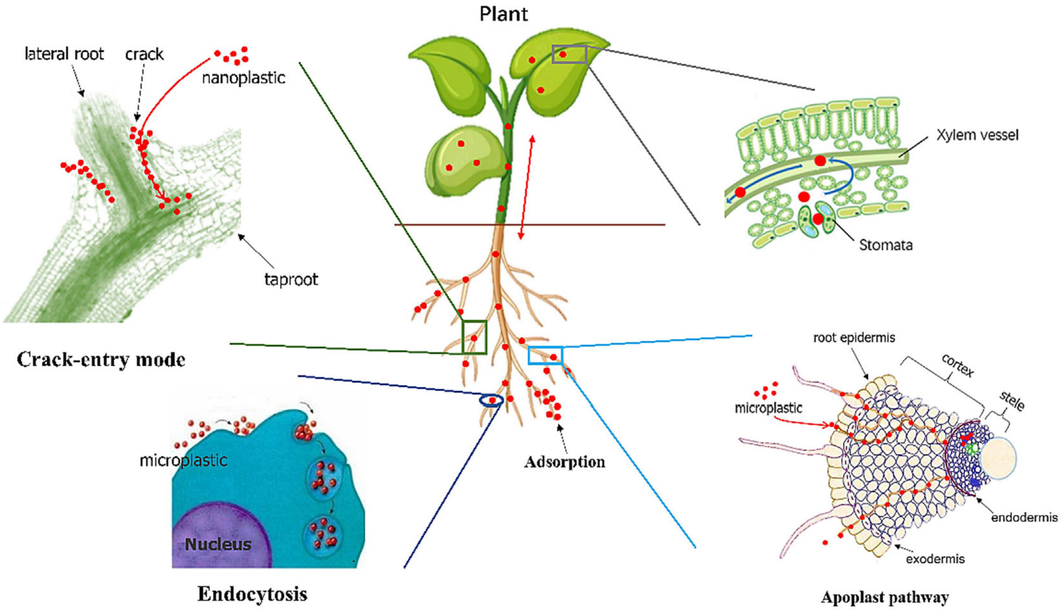

Figure 3. Several mechanisms of MNPs particle entry into plant tissue (Yu et al., 2024)

has reached critical levels, with microplastic abundance reported to range from 3.7 to 40,800 particles per kilogram of soil (Nguyen et al., 2025). One of the main pathways for MNPs entry into the soil is from the air and urban road sources, which are the primary contributors to MNPs (Beaurepaire et al., 2025; Amato-Lourenço et al., 2025).

Exposure to MNPs significantly affects the morphology and physiological functions of rice leaves, particularly in relation to the photosynthesis process. Xu et al. (2024), through transcriptomic analysis, showed that exposure to polystyrene micro nanoplastics suppresses the expression of genes involved in the chlorophyll biosynthesis pathway, photosynthesis, and sucrose metabolism in rice leaves. The suppression of these gene expressions disrupts the photosynthetic process, ultimately leading to a reduction in green biomass accumulation, manifested as a decrease in the canopy area.

In rice leaves, the effects of MNPs are primarily observed as a reduction in biomass and photosynthetic function, although changes in leaf shape have been less studied. Liu and Shen (2024) reported that chronic input of polystyrene microplastics reduced fresh leaf weight by approximately 64%, accompanied by a decrease in leaf chlorophyll content. Wu et al. (2020) also showed that rice canopy biomass (including leaves) decreased by 13–40% at high polystyrene MNPs doses. The accumulation of important metabolites in leaves (amino acids and sugars) also decreased due to MP. Therefore, although leaf morphological parameters such as length and width are not extensively reported, these results indicate that rice leaves on plants exposed to MNPs tend to be smaller in number or smaller in size as physiological leaf development is disrupted (Liu and Shen, 2024; Wu et al., 2020).

Once in the soil, MNPs can migrate vertically to a depth of 100 cm, although the quantity and size (Figure 1) decrease with increasing depth (Zhang et al., 2024). This contamination is not only physical but also chemical. MP can alter soil structure, texture, and hydraulic properties, as well as affect the physico-chemical and biological characteristics of soil (En-Nejmy et al., 2024). The impacts include disrupted plant metabolism, changes in growth, and disruption of the rhizosphere microbial community (Ranauda et al., 2024). Furthermore, research indicates that exposure to MNPs can cause shifts in soil microbial communities and impact the survival of soil fauna such as earthworms, nematodes, and collembola.

The impact of micro- and nanoplastics on rice plant stems, height, and biomass

Exposure to polyethene MNPs significantly inhibits rice stem growth, as evidenced by decreased stem length and mass (Wu et al., 2023). This disruption is closely related to reduced photosynthetic activity and metabolic efficiency due to plastic-induced stress. In a study involving a combination of polyethene MNPs and arsenic, Zhou et al. (2021) noted a 32.6–54.6% reduction in stem biomass, indicating that MP has a strong potential to reduce stem tissue growth, even with additional stress factors. This inhibitory mechanism is suspected to be related to disruptions in hormonal pathways, particularly auxin, which plays a crucial role in stem elongation processes.

In addition to stems, rice plant height decreased significantly due to exposure to MNPs. Xu et al. (2023) reported that the application of polystyrene (PS) MP caused a dose-responsive decrease in plant height, reaching 27% at high concentrations. Similar results were found by Wu et al. (2023), who showed that exposure to polystyrene MNPs for 21 days reduced plant height by 12–27%, depending on the MP concentration in the medium (50–500 mg/L). This reduction was consistent with inhibited root and leaf growth, as well as decreased photosynthesis required to support stem elongation. Yang et al. (2022) also noted that the use of PE- and PBAT-based plastic mulch significantly reduced rice plant height, indicating that even conventional agricultural plastics can cause negative physiological effects.

Reduced plant biomass is another major impact of plastic stress. Various studies have shown that MNPs reduce dry matter accumulation, both in shoots and roots. Ma et al. (2022) reported that PS and PVC MNPs treatments in a hydroponic system significantly reduced plant fresh weight and dry weight. Wang et al. (2022) found that polystyrene MNPs caused a 13.59% reduction in plant fresh weight compared to the control, and reduced shoot dry weight by up to 71%, depending on the type of plastic chemical modification. Wu et al. (2023) also noted a 13.1–40.3% reduction in total plant biomass after 21 days of treatment with polystyrene MNPs. This reduction in biomass accumulation indicates that the plant's capacity to synthesize and store dry matter is disrupted, which could ultimately limit carbon distribution to generative organs such as grains. Overall, these findings suggest that exposure to

MNPs negatively impacts the vegetative growth phase of rice plants through inhibition of stem elongation, reduced plant height, and decreased biomass accumulation. These effects are likely mediated by physiological disturbances, reduced photosynthetic efficiency, and hormonal imbalances, which synergistically reduce rice productivity in plastic-contaminated environments.

Morphological response of rice plant roots

Exposure to MNPs generally disrupts the development of the root system in rice plants. Zhou et al. (2021) found that polystyrene MNPs reduced the length of the main root while stimulating the formation of more lateral roots in rice seedlings. Another study reported that exposure to PS MNPs significantly reduced the fresh weight, dry weight, and root length of rice plants compared to control plants. These changes indicate shorter roots and impaired root systems, with necrosis occurring at the root tips even at high MNPs concentrations (Liu et al., 2022). Thus, MNPs disrupts rice root morphology through oxidative stress and nutrient uptake inhibition (Liu et al., 2022; Zhou et al., 2021).

Final impact on rice productivity and yield

The effects of MNPs on rice grain yield show significant variation depending on environmental conditions and a variety of genetics. A study by Guo et al. (2023) revealed that the combination of heat stress with LDPE or PLA MNPs reduced grain yield by approximately 32% due to disruptions in photosynthesis and nitrogen metabolism. Varietal responses to MNPs exposure also vary. Yi et al. (2023) found that the hybrid variety Jiafengyou 6 experienced a 23% reduction in grain yield due to polyethene type MNPs, while the local variety Nangeng 5055 showed no significant reduction under the same conditions. Similar findings were reported by Wu et al. (2022), who noted that PS-MP reduced grain yield by 10.6% in one cultivar but increased yield by 6.4% in another cultivar, indicating cultivar-specific physiological heterogeneity. Conversely, Wu et al. (2024) reported that exposure to a certain amount of PE MNPs did not significantly affect grain yield in either conventional or hybrid varieties. Physiologically, this reduction in rice yield is generally associated with root system damage, impaired water and nutrient uptake, reduced leaf area and chlorophyll content, and hindered grain filling due to hormonal disruption and decreased photosynthetic efficiency (Guo et al., 2023; Yi et al., 2023). However, some studies have noted that nitrogen content in rice grains remains stable or even increases, indicating a complex and non-linear response to MNPs concentration and type. Thus, stress accumulation caused by MP and NP – through morphological, physiological, and hormonal changes – can synergistically reduce rice grain yield, although the extent of the impact is greatly influenced by environmental conditions, plasticity, and genetic characteristics of the variety (Guo et al., 2023; Wu et al., 2022; Wu et al., 2024; Yi et al., 2023).

Physiological and biochemical responses of rice to micro- and nanoplastic stress

Photosynthesis

Some studies report that MNPs reduces rice's photosynthetic capacity. Yang and Gao (2022) found that exposure to MNPs from PBAT (biodegradable) and PE (polyethene) mulch films both suppressed net photosynthesis rates and SPAD values (chlorophyll) in rice leaves, with polyethene MNPs having a stronger effect. Nitrate and ammonium transporter genes in roots were also repressed, indicating that MP affects N metabolism and photosynthesis. Ma et al. (2022) reported that exposure to PS-MP and PVC-MP (1.5–3.0 mg/L) reduced photosynthesis rates by ~31–44% and lowered SPAD values by approximately 35% compared to controls, with PVC-MP being more toxic than PS-MP. Wang et al. (2022) also observed a decrease in biomass and photosynthetic capacity (plant height and dry weight decreased drastically) in three surface functional groups (PS, PS-COOH, PS-NH_2) when exposed to polystyrene nanoplastics (PS-NP). All these studies indicate that MNPs reduces photosynthesis (chlorophyll/SPAD) in rice.

Antioxidant enzyme activity

MNPs consistently induces oxidative stress in rice, as evidenced by increased antioxidant enzyme activity. Ma et al. (2022) reported that exposure to PS/PVC-MP (3.0 mg/L) significantly increased SOD (109–146%), POD (232–289%), and CAT (183–243%) compared to the control, alongside increases in MDA and H_2O_2. Liu et al. (2022) also found that SOD and POD activity in rice roots sharply increased after exposure to

PS-MP (10–40 mg/L). Wang et al. (2022) reported that all PS-NP treatments activated the rice antioxidant system (increased gene expression and enzyme activity of SOD/POD). Lu et al. (2023) noted significant activation of all major antioxidant enzymes (SOD, POD, CAT, APX) in rice upon exposure to PS-NP (50–200 mg/L), indicating oxidative stress. Overall, MNPs (PS, PVC, PE) increased SOD, POD, CAT (and APX) activity in rice plants, though the extent of the increase depended on the type of plastic and concentration.

Plant hormones

MNPs exposure also modulates hormone metabolism in rice. Zhou et al. (2021) reported that PS nanoplastics inhibit jasmonic acid biosynthesis in rice roots (along with lignin), resulting in a significant reduction in jasmonate levels. This means that MNPs stress reduces jasmonic acid defence hormones. A combined study of PS-MP with phenanthrene (Wang et al., 2022) showed that MNPs can alter plant hormone signal transduction pathways, although specific hormone parameters other than jasmonic acid have not been extensively reported. There have been no explicit reports on other hormones (auxin, ABA, ethylene) for rice in the past five years.

Nutrient absorption

MNPs disrupts the absorption of nutrients and heavy metals. Ma et al. (2022) showed that PVC/PS-MP reduces ionic balance: the concentrations of Ca, N, P, and K in roots and leaves become imbalanced at high doses. Yang and Gao (2022) found that nitrate/ammonium transporter genes in rice roots are repressed by MP (vegetative phase), suggesting that N absorption is disrupted. Liu et al. (2022) observed that PS-MP (40 mg/L) accelerates Cd accumulation in rice roots. This means that MP (especially PS) can increase heavy metal (Cd) absorption when present together. In general, MNPs (PE, PS, PVC, PBAT) tend to inhibit N, P, and K absorption and worsen heavy metal accumulation in rice (Ma et al., 2022; Liu et al., 2022).

Primary and secondary metabolite profiles

MNPs induces changes in metabolites in rice. Zhou et al. (2021) noted that PS-NP enhances carbon metabolism: soluble sugar content in rice roots increases significantly. However, simultaneously, the biosynthesis of jasmonic acid and phenylpropanoids (lignin) is suppressed. Conversely, Ouyang et al. (2024) reported that PS-MNPs (100 mg/L) inhibits amino acid pathways (arginine, alanine, asparagine, glutamate) and activates phenylpropanoid pathways (including lignin) in rice roots. This is reflected in reduced root protein content and increased lignin. In other words, MNPs alters the primary (amino acids, sugars) and secondary (phenols, lignin) metabolism of rice plants (Ouyang et al., 2024). Previous metabolomic studies (Wu et al., 2020) also found changes in amino acid, carbohydrate, and phenol profiles in rice exposed to PS-MNPs. Overall, MNPs exposure in rice disrupts primary metabolites (carbohydrates, amino acids) and secondary metabolites (phenols, lignin), with a tendency toward the reduction of certain metabolites and compensation through the phenylpropanoid detoxification pathway (Zhou et al., 2021; Ouyang et al., 2024).

Molecular response of rice to micro- and nanoplastic stress

Oxidative stress and antioxidant defense

MNPs inhibits nutrient transport pathways in plants and can enter vascular plants, causing more complex effects. MNPs abrasion likely triggers ROS (reactive oxygen species) production by increasing superoxide (O_2^-), hydrogen peroxide (H_2O_2), and hydroxyl radical ($OH\cdot$) production. MNPs can interact with tissues and internal compounds, increasing ROS production. ROS damages lipid membrane structures, cytolytic proteins, and cellular DNA, disrupting plant physiological homeostasis. Jin et al. (2025) and Xu (2024) reported that increased ROS levels correlate with the activation of redox stress pathways, particularly in root tissues. These changes are characterized by a surge in malondialdehyde (MDA) content, an indicator of lipid peroxidation and membrane damage. Increased ROS triggers the plant's antioxidant defence system, including superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and ascorbate peroxidase (APX). Increased SOD aims to dismutate superoxide into H_2O_2, while CAT and APX degrade H_2O_2 into water and oxygen to reduce oxidative damage potential. Lu et al. (2023) and Jiang et al. (2024) reported a 1.5–2-fold increase in SOD and APX in rice roots after MNPs exposure, indicating the presence of a molecular compensation mechanism against ROS accumulation.

Hormonal signaling pathways

Hormonal signalling pathways are small molecules that regulate growth, development, and physiological responses. The five endogenous hormones in plants are auxin, cytokinin, gibberellin, abscisic acid (ABA), and ethylene. The phytohormones ABA, auxin (IAA), JA, SA, and ethylene play a role in plant defence against MNPs stress. MNPs stress triggers changes in endogenous hormones in rice plants, affecting vegetative growth, root formation, and the plant's tolerance to stress. Jin et al. (2025) reported that MNPs stress reduces auxin levels and increases ABA, which inhibits root elongation. The increase in ABA is marked by the expression of the OsNCED3 gene (ABA biosynthesis) and OsPYL5 gene (ABA receptor), while the decrease in auxin is marked by the expression of the OsPIN2 and OsPIN9 genes (Wang et al., 2022). The transcription factors OsARF16 and OsARF19 were inhibited after 24 hours of MNPs stress. The hormones JA, SA, and ethylene, which are defence hormones, increased under MNPs stress. Jin et al. (2025) reported an increase in the expression of the OsLOX2 and OsAOS1 genes (JA biosynthesis) in response to stress, with increased gene expression acting as a mediator of plant resistance to external toxicity. Increased ethylene hormone levels were indicated by the expression of the OsACO1 gene (ACC oxidase), leading to accelerated senescence and reduced plant vigour (Wu et al., 2021).

Stress-responsive transcription factors

MNPs stress causes increased oxidative stress and hormonal disruption, activating a complex gene expression regulatory system in rice plants. Transcription factors (TFs) function as molecular regulators that integrate environmental stress signals with the regulation of plant physiological and molecular responses. WRKY, NAC, DREB, MYB, and bZIP transcription factors exhibit altered expression under MNPs stress, regulating plant defence signalling and metabolism. WRKY transcription factors act as primary regulators in governing biotic and abiotic stress responses by binding to W-box elements (TTGACC/T) in target gene promoters and mediating defence gene activation. Imran et al. (2024) reported increased expression of the OsWRKY45, OsWRKY72, and OsWRKY76 genes in rice roots under MNPs stress. The NAC transcription factor (NAM, ATAF1/2, CUC2) acts as a primary regulator in controlling responses to dehydration, salinity, and ROS. Wang et al. (2022) reported the activation of OsNAC2 and OsNAC6 within 48 hours after MNPs treatment. The OsNAC6 gene plays a role in strengthening cell walls and increasing the expression of antioxidant genes such as OsCATB and OsAPX2. NAC transcription factors play a crucial role in regulating root morphogenesis and tissue differentiation, making NAC genes potential candidates for developing stress-tolerant varieties based on transcriptional regulation. DREB (Dehydration Responsive Element Binding) transcription factors act as regulators in responding to dehydration signals and ROS by stabilizing membranes and protecting proteins under stress. Xu (2024) reported increased expression of OsDREB2A and OsDREB1C in rice roots exposed to PS-NPs. The MYB transcription factor acts as a regulator in responding to MNPs stress in the biosynthesis of secondary metabolites such as flavonoids and lignin. Jiang et al. (2024) reported that the genes OsMYB4 and OsMYB30 showed increased expression under MNPs stress. The OsMYB30 gene is involved in the biosynthesis of lignin and flavonoids, which function to strengthen cell wall structure and provide natural antioxidants against ROS. The bZIP (basic leucine zipper) transcription factor acts as a regulator in controlling responses to the integration of hormonal ABA and redox signals through promoter elements such as ABRE and G-box. Xu (2024) reported increased expression of OsbZIP23, OsbZIP46, and OsABI5 in rice roots after MNPs treatment. The OsbZIP46 gene is the primary regulator of ABA and functions as a physiological response to stress by linking ABA accumulation, activation of the antioxidant defence system, and increased expression of survival genes such as LEA (Late Embryogenesis Abundant).

Proteomic and metabolomic changes

MNPs stress induces systemic modifications at the proteomic and metabolomic levels in rice plants. Proteomics shows a decrease in proteins involved in photosynthesis. Jiang et al. (2024) reported that NP reduced 40% of photosystem proteins (PsbA and PsbB) and the enzyme Rubisco (ribulose-1,5-bisphosphate carboxylase) in leaf tissue. The decrease in protein expression disrupts carbon fixation efficiency and energy metabolism. Metabolomic changes accompanying proteomic responses include increased accumulation of phenolic compounds and flavonoids, known to act as natural antioxidants. LC-MS/MS-based metabolomics conducted by Imran et al. (2024)

identified increased levels of compounds such as kaempferol, quercetin, and chlorogenic acid in root tissues. These compounds have a high capacity to eliminate ROS and strengthen cell wall structure through lignification processes. Zhang et al. (2024) detected an increase in lignin metabolites through the activation of the phenylpropanoid pathway, marked by the upregulation of the enzymes PAL (phenylalanine ammonia lyase), C4H (cinnamate 4-hydroxylase), and 4CL (4-coumarate-CoA ligase). This pathway is the main foundation for lignin formation and flavonoid biosynthesis as part of the plant defence system. MNPs stress increases the biosynthesis of alkaloids and other metabolites that are toxic to pathogens, such as berberine and solavetivone. These metabolites have anti-pathogenic activity and are part of the arsenal of secondary metabolites in rice in response to external stress. At the same time, there is an increase in redox metabolites such as glutathione (GSH) and ascorbic acid (ASA) as a compensatory response to the reported decrease in antioxidant enzyme activity of SOD and CAT under conditions of excessive ROS production (Jiang et al., 2024).

Signal transduction pathways

Signal transduction pathways act as early detection and propagation of molecular signals in response to environmental stress, including MNPs stress. MNPs stress on rice plants induces responses through the activation of redox, calcium (Ca^{2+}), and protein kinase signalling systems, including the mitogen-activated protein kinase (MAPK) and calcium-dependent protein kinase (CDPK) pathways.

Table 1. Proposed mitigation strategies against micro- and nanoplastic-induced stress in rice and their monitoring indicators

Reported mechanism	Proposed mitigation strategies	Monitoring indicators	Sources
Reduced chlorophyll content & downregulation of photosynthetic genes → ↓ photosynthesis, ↓ canopy	Targeted fertilization (N, Mg); SPAD-based monitoring; optimization of light and irrigation	SPAD/chlorophyll content; photosynthetic rate; expression of chlorophyll biosynthesis genes; biomass	Liu and Shen (2024); Xu et al. (2024); Yang and Gao (2022)
ROS accumulation and lipid peroxidation (↑MDA) with altered antioxidant enzyme activity	Micronutrient supplementation (Zn, Mn, Cu, Fe); antioxidant priming (GSH/ASA precursors); inoculation with PGPR enhancing oxidative tolerance	MDA, H_2O_2; SOD/CAT/APX activity; GSH/ASA levels	Ma et al. (2022); Lu et al. (2023); Jiang et al. (2024)
Root growth impairment (shorter length, lateral proliferation, necrosis)	PGPR inoculation producing IAA; organic amendments; irrigation management	Primary root length; lateral root number; root necrosis; nutrient uptake	Zhou et al. (2021); Liu et al. (2022)
Hormonal imbalance (↓IAA, ↑ABA, JA/SA/ET) → growth disruption and accelerated senescence	PGPR producing IAA; controlled hormonal priming; water and nutrient management to reduce ABA accumulation	Hormone levels (IAA, ABA, JA, SA, ET); expression of OsNCED3, OsPINs, OsLOX2; senescence rate	Wang et al. (2022); Jin et al. (2025); Wu et al. (2021)
Nutrient uptake disruption (N, P, K) and heavy metal (Cd) accumulation	Soil-test-based fertilization; pH adjustment; crop selection; microbial inoculants reducing metal bioavailability	Concentration of N, P, K, Cd in tissues; expression of nutrient transporters	Ma et al. (2022); Yang and Gao (2022); Liu et al. (2022)
Decline in photosystem proteins and Rubisco → ↓ biomass and yield	Nutrient supplementation (N, Mg); environmental management; breeding for tolerant cultivars	Abundance of Rubisco/Psb proteins; photosynthetic rate; biomass; grain yield	Jiang et al. (2024); Liu and Shen (2024); Wu et al. (2023)
MNPs input via mulch, irrigation, or atmospheric deposition → soil accumulation	Reduce fragmented plastic use; filtration of irrigation water; improved plastic waste management in agriculture	MNP concentration in soil (particles·kg^{-1}); vertical distribution; irrigation/ atmospheric inputs	Omotola and Supriyanto (2024); Beaurepaire et al. (2025); Zhang et al. (2024)
Altered metabolomic responses (sugars, amino acids, phenylpropanoids) → detoxification/adaptation	Application of elicitors (e.g., chitosan) to enhance phenylpropanoid pathway; selection of genotypes with protective metabolic profiles	Sugar/amino acid levels; flavonoids (kaempferol, quercetin); activity of PAL/ C4H/4CL enzymes	Ouyang et al. (2024); Imran et al. (2024); Zhang et al. (2024)
The interactions between soil, microplastics, biochar, and microbial communities form a complex web that influences soil health and plant productivity	microbially loaded biochar in reducing the negative impacts of MNPs on soil nutrition and plant biomass	oxidative stress levels, decreased malondialdehyde levels and moderately increased antioxidant enzyme activity	Afzal et al. (2025)

Increased ROS, particularly H_2O_2 and O_2^-, function as the primary signals that activate signal transduction pathways. ROS acts as signalling molecules that modulate the activity of various sensor proteins, such as receptor-like kinases (RLKs) and leucine-rich repeat kinases (LRR-RLKs). Imran et al. (2024) reported increased expression of RLKs such as OsWAKL21 and OsLRK10L2 in rice root tissues exposed to PS-MNPs, indicating the initial activation of the sensing pathway for stress molecules. The activation of RLKs triggers the phosphorylation of downstream protein kinase cascades, such as MAPK and CDPK. MAPK (OsMPK3, OsMPK6, and OsMKK4) undergo expression induction and phosphorylation activation. Xu (2024) reported that OsMPK6 was phosphorylated within the first 3–6 hours after NP exposure, along with increased expression of OsWRKY45 and OsDREB2A as downstream transcription targets. MAPK activation enhances the expression of defence genes such as PR1, OsAPX2, and OsbZIP23, which play a role in mitigating oxidative and hormonal stress. CDPK acts as a signal transducer dependent on fluctuations in Ca^{2+} ion concentration in the cytosol. MNPs stress causes a rapid increase in intracellular Ca^{2+} ions through channels such as cyclic nucleotide-gated channels (CNGCs). Wang et al. (2022) reported increased expression of OsCNGC14 and OsCDPK7, which triggered the activation of cell protection gene transcription and secondary cell wall formation. CDPK regulates the expression of lignification enzymes (PAL, 4CL, CAD) and mediates the expression of HSP proteins through the phosphorylation of HSFs (heat shock transcription factors).

Mechanism-based mitigation approaches

Table 1 summarizes the key physiological and molecular mechanisms reported in rice under MNPs exposure, along with potential mitigation strategies, measurable monitoring indicators, and corresponding literature sources. This framework provides a comprehensive reference for linking observed stress responses with targeted agronomic or biotechnological interventions.

CONCLUSIONS

MNPs exposure negatively impacts rice growth and productivity through three interrelated levels of effects: (1) morphological—reduced leaf, stem, and root biomass and altered root architecture; (2) physiological—decreased photosynthesis, impaired nutrient uptake, ROS accumulation, and activation of the antioxidant system; and (3) molecular—hormonal disruption (e.g., ↓IAA, ↑ABA, ↑JA/SA/ET), altered transcription factor expression (WRKY, NAC, DREB, MYB, bZIP), and proteomic and metabolomic changes (decreased photosynthetic proteins, increased phenolics/lignin). The impact on grain yield is variable and depends on the polymer type, particle size, dose, environmental conditions, and genetic traits of the rice variety.

While experimental evidence indicates a clear risk to sustainable rice production, current studies have important limitations: many experiments use pristine plastic particles that do not represent the degraded/compounded forms of MNPs in real fields; there is a lack of long-term studies and field trials; and the lack of standardized protocols (polymer type, size, dosage). The interactions between MNPs and other environmental stressors (drought, salinity, heavy metals) and advanced molecular mechanisms (hormonal crosstalk, epigenetic regulation, distant signaling) remain inadequately understood.

Future research and mitigation efforts require the integration of long-term field studies with a multi-omics approach, consistent testing standards, and testing of aged/environmentally modified MNP particles. Promising mitigation strategies include improved plastic waste management and the use of certified plastic-free compost, irrigation water filtration, the development of biodegradable mulches, the breeding of MNP-tolerant varieties, and agronomic and microbiological interventions (PGPR, micronutrient supplementation, phenylpropanoid elicitors).

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