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Nanotechnology for Climate Resilience in Rice (*Oryza sativa*): A Review of Current Applications and Future Directions

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Abstract: Rice is the most consumed cereal crop in the world. The demand for rice is increasing day by day as the global population grows and agricultural land becomes more limited. In addition, rice production has been affected by many climate issues. One abiotic issue affects rice production in many parts of the world. To adapt rice to issues such as drought, salinity, heavy metals, cold, and heat stress, farmers use many conventional techniques, such as their perception, following deadlines, and the use of other toxic chemicals that are harmful to the environment and living beings. Despite using those methods, they do not achieve the desired rice yield due to these climate issues. Nanotechnology has become the most effective way to address many issues, including abiotic ones. In this review, we highlighted how nanotechnology increases rice production through climate adaptation; the issues affecting rice growth and adaptation; traditional methods to mitigate climate-related issues; how non-fertilizers improve rice growth (up to 70%); the limitations of nanotechnology; their environmental effects; and the future of nanotechnology.

Keywords: rice yield; nanotechnology; abiotic stress; nanoparticles; sustainable agriculture; crop resilience and adaptability.

1. Introduction

Rice is one of the most widely consumed staple foods, and it is the cereal crop that has been cultivated for thousands of years; in addition, it is a primary source of carbohydrates for many people around the globe. It has been cultivated in over 114 countries and plays an important role in global food security.

Climate change has become a threat to rice production around the globe as its nature changes over time. With climate change, biotic and abiotic stresses, such as temperature fluctuations, are strongly affecting rice productivity and rainfall patterns[1]. Therefore, climate change negatively affects rice production and threatens global food security as the global population grows and agricultural land becomes more limited [2]. Farmers use many conventional and ongoing strategies to adapt to these climate issues, such as changing planting times and using weather forecasts[3].

However, conventional practices cannot completely mitigate climate change, resulting in a decrease in rice production day by day, and it is going to be a major threat to global food security, as it is the second-most-consumed food in the world. Nanotechnology plays a crucial role in rice production due to its small particle size (0-100 nm), which makes it a 'magic bullet' with substantial effects across various sectors, particularly in crop development. As nanoparticles have a tiny size, plants can penetrate them very effectively as compared to bulk material [4].

All crops, particularly rice, are affected by many climate issues, for example, soil salinity [5–8], water stress diseases[9–12], etc. Seed nano-priming with ZnO-NPs plays a significant role in mitigating both drought and water stress and in improving rice productivity by enhancing agronomic traits. In this study, six treatments were used, such as 0, 5, 10, 15, 25, and 50 ppm by applying the rice seed. The most effective result was found at 25 ppm for drought and irrigated land. This study plays a significant role in the climate adaptation of rice, especially under salinity, drought [13–16], and water stress [17].

Another research conducted to assess the yield performance of nano-CuO and nano-ZnO micronutrient fertilizers applied with four treatments, which are (T0) control, nano-CuO 60 mg L^{-1} (T1),nano-ZnO 30 mg L^{-1} (T2), and nano-CuO-ZnO composite 120 mg L^{-1} (T3). The nano fertilizer was applied by foliar spray after 48 -58 days of sowing and 100-105 days in the filling stage. A significant increase was observed with the application of CuO and ZnO nonfertilizers, with growth parameters and grain yield of rice plants increasing in thespecific rice varieties Bg360, BW364, Kalu Heenati, and Kuruluthuda [18].

This review highlights the issues of rice growth and adaptation, traditional methods to mitigate climate change, and their environmental effects. Moreover, described how nanotechnology helps mitigate climate-related problems in various rice crops, including their effects and treatments. This paper also focused on nonfertilizers, their application strategies on different rice varieties, and their significant result on rice yield.

2. Issues for Rice Growth and Adaptation to the Environment

Rice (*Oryza sativa*) production faces many challenges that impact yield growth and adaptation. One of the primary concerns is the decline in rice yields caused by biotic stresses [19–21], for instance, pests, diseases, and weeds [22,23]. Many insects, such as stem borers, leaf folders, and planthoppers, can cause significant yield losses if they are not adequately managed. Diseases, for example, blast [24], bacterial leaf blight [25–28], and sheath blight [29–31] also pose a threat to rice production. In addition, weed competition can minimize yield performance by competing for resources. Effective pest and disease management techniques, along with efficient weed control measures, are crucial for sustaining rice yieldsn many regions [32].

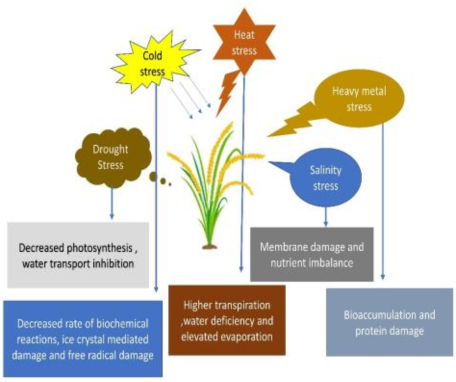


Figure 1. Variety of abiotic stresses and their physiological effects on rice plants.

Abiotic stresses also reduce rice growth and adaptation. Drought stress is a critical factor affecting rice cultivation and reduces water availability by impairing plant growth and development. Climate change changes in rainfall patterns [33–37] and increased temperature [38,39]. Another abiotic stress is salinity, which adversely affects rice productivity, particularly in coastal areas and regions with poor drainage. High levels of soil salinity hinder water uptake and inhibit nutrient absorption, resulting in stunted growth and mitigated yield. Moreover, heavy metal toxicity [40–44] is a growing concern in rice cultivation due to soil contamination from industrial activities and the use of agrochemicals across various rice lands. Elevated levels of heavy metals, such as cadmium and arsenic, can accumulate in rice grains and pose health risks to consumers. Describing these abiotic stresses is crucial to ensure the adaptability and productivity of rice crops [45].

The limitation of arable land presents another challenge for rice cultivation. As urbanization and industrialization increase, agricultural land is increasingly converted to non-agricultural uses. In addition, soil degradation [46,47], erosion, and nutrient depletion further decrease the availability of fertile land for rice cultivation. Sustainable land management methods, including soil protection measures, efficient land use planning, and land reclamation, are essential for maintaining and expanding rice production areas [48].

The necessity of sustainable agricultural methods is becoming increasingly critical. Traditional rice farming practices often rely on excessive use of chemical fertilizers and pesticides, which can harm the environment and human health. Intensive use of agrochemicals can lead to soil degradation, water pollution [49], and the emergence of pesticide-resistant pests and diseases. It is important to transition towards sustainable and environmentally friendly approaches such as integrated organic farming, pest management [50,51], and precision agriculture [52,53]. These methods stimulate the efficient use of resources, reduce chemical inputs, and improve the ecological balance of rice ecosystems [54].

To address these challenges, nanotechnology offers potential solutions to improve rice growth and adaptation. Nano fertilizers [55–60], nanosensors [61,62], nano pesticides [63–65], and nanomaterials have shown substantial results in addressing issues related to nutrient availability, pest and disease management, nutrient and water use efficiency, and stress tolerance. Nanofertilizers are loaded with essential nutrients that can enhance nutrient uptake and utilization efficiency, thereby improving crop productivity and yield [66]. Nanopesticides provide targeted delivery and controlled release of active components, minimizing chemical usage while improving pest and disease control [67]. Nanosensors enable real-time monitoring of soil conditions, plant health, and environmental parameters, enabling precise irrigation and nutrient management systems [68]. Nanomaterials have unique properties that can reduce the adverse effects of abiotic stresses such as salinity, drought, and heavy metal toxicity by enhancing stress tolerance in rice plants [69].

Addressing the issues related to rice growth and adaptation is essential for maintaining food security and sustainable agriculture. Biotic stresses, limited arable land, abiotic stresses [70–72], and the need for sustainable techniques present substantial challenges. Nanotechnology promotes significant avenues for addressing these challenges by improving nutrient availability, disease management and pest control, resource efficiency, and stress tolerance. However, it is important to consider the potential limitations and environmental impacts of nanotechnology, including nanoparticle toxicity, scalability, and regulatory framework.

3. Traditional Methods to Mitigate Climate Issues

To address the challenges of rice growth and adaptation, traditional methods offer many strategies that have been employed over the centuries. Biotic stresses, such as pests, weeds, and diseases, have traditionally been managed through integrated pest management (IPM) [73]. These methods include combining biological control agents, cultural practices, and the proper use of pesticides. Trap cropping, crop rotation, and biological control agents, such as beneficial insects and microbial biopesticides, are key components of IPM strategies in rice and other crop cultivation. These strategies help minimize pest and disease outbreaks, reduce chemical inputs, and restorecological balance in rice ecosystems [74].

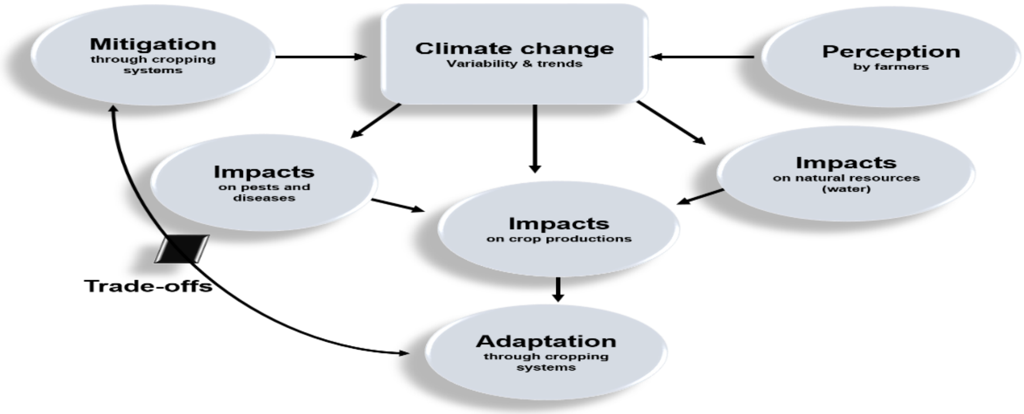


Figure 2. Traditional actions to reduce vulnerability to climate issues.

For abiotic stresses such as salinity and drought, traditional water management strategies have been proven effective. In areas prone to water scarcity, traditional irrigation systems such as furrow irrigation [75–77], bunded fields, and raised bed systems help protect water and ensure efficient distribution to rice plants. Traditional practices such as intermittent flooding and alternative wetting and drying (AWD) [78,79] are also implemented to conserve water while maintaining crop productivity. In addition, locally adapted and traditional landrace varieties that demonstrate tolerance to abiotic stresses are utilized to increase adaptability and resilience [80].

The availability of arable land is addressed by traditional land management strategies. Terrace farming practiced in hilly regions helps to create flat cultivation areas, decreases soil erosion, and stimulates land use. Generally, traditional soil conservation methods, including contour plowing, strip cropping [81], and contour bunds, effectively mitigate soil erosion and balance soil fertility. Farmers also use organic materials, such as farmyard manure and compost, to replenish soil nutrients and improve soil structure. Furthermore, agroforestry systems in which rice is intercropped with trees or other crops help optimize land use and promote sustainable agricultural practice[82].

Sustainable agricultural methods are an integral part of traditional rice farming systems. Organic farming practices, depending on natural inputs and avoiding synthetic chemicals, are used by a lot of farmers.

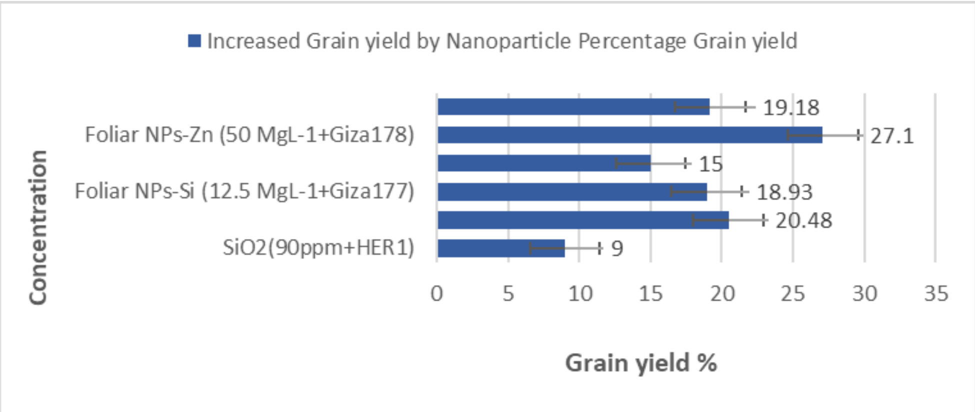
Traditional knowledge and methods, for instance, the use of crop residues, cover crops, and biofertilizers, contribute to pest control, soil fertility, and nutrient management. Moreover, crop diversification and traditional approaches are adopted to reduce pest and disease pressure, enhance resource use, and improve agroecosystem resilience. Furthermore, traditional rice-fish farming systems, in which fish are integrated into rice paddies, offer mutual benefits, such as pest control andn additional source of protein [83].

The preservation and use of traditional rice cultivars and local varieties are important for adapting to changing environmental conditions. These traditional varieties often contribute to genetic diversity and traits that offer tolerance to specific stress. Farmers and scientists collaborated to protect and utilize the traditional varieties through participatory plant breeding and seed exchange programs. This method helps to maintain agrobiodiversity, improves adaptability, and optimizes sustainable rice production [84].

In a nutshell, traditional methods confer valuable techniques to address the challenges of rice growth and adaptation. Integrated pest management methods, sustainable land management practices, traditional water management techniques, organic farming methods, and the preservation of traditional rice landraces help to mitigate biotic and abiotic stresses, optimize resource utilization, and increase resilience in rice ecosystems. Integrating traditional pieces of knowledge with modern scientific tools can lead to sustainable and resilient rice farming systems.

4. Nanotechnology Maintained Rice Adaptation to the Environment

Climate adaptation by nanotechnology has been a promising factor in recent years. The bar chart represents nanoparticle-assisted grain yield using different concentrations and rice cultivars. Here, we can see nano ZnO priming with 25 ppm on IRRI-6 variety has given 19.18% grain yield [17], whereas 27.1% grain yield was found from the foliar spray of Zn-NPs with a concentration of 50 mgL^{-1} on Giza178. However, the Foliar spray of Si-NPs on (2.5 MgL^{-1}) Giza178 has given a 15% grain yield compared to the control [85]. Again, Foliar spraying of Si-NPs (12.5 mgL^{-1}) on Giza177 has augmented 18.93% grain yield, and soaking with Se-NPs on Giza177 obtained 20.48% [86]. In the end, SiO_2 (90 ppm) on the HER1 variety showed the lowest result, 9% among the others [87].



Graph 1. Enhanced rice grain yield by using different types of nanoparticles.

Rice is a key crop to ensure food security around the globe. It is affected by many climatic factors, such as drought and salinity. However, nanotechnology is the pledge that can combat these issues, resulting in smart rice yield. Seed priming with ZnO-NPs has shown a significant improvement in both water-stress conditions and irrigated land for the rice variety (IRRI-6). There were five treatments: 0, 5, 10, 25, and 50 ppm used, respectively, and the best contribution was found from 25 ppm. Nano-primed ZnO-NPs developed the agronomic profiles as well as mitigated the drought stress of rice (*Oryza sativa L*). There is still a great deal of work to be done in this research; for example, it needs to be implemented in other crops and agricultural fields [88]. Another, most challenging factor for rice crops is to grow on cadmium and high salt-affected soil. To come up with this issue, CeO_2-NPs were treated in a hydroponic medium to evaluate the effect they had on cadmium-contaminated and high-salt soil for one week's rice seedlings. This result shows that the application of CeO_2-NPs activated antioxidant defense by lowering proline levels. It can be estimated that using CeO_2-NPs in agriculture decreased the stressor, which is the main inhibition of cultivation, particularly rice. However, no field experiments were found in this research, and other crops except rice [89]. Cadmium is an unimportant toxic trace element that affects rice growth and adaptation, apparently for rice. A group of researchers conducted a study on rice using foliar applications of TiO2 and Si-NPs across five treatments, including a control. Both nanoparticles were treated separately after translating seven-day intervals in the field with concentrations of 0, 5, 10, 15, and 20 mgL^{-1}. The key result of that study comes from Si-NPs rather than TiO_2-NPs with the increase of each concentration of nanoparticles by foliar spraying. These NPs significantly reduced Cd concentrations in rice tissues, and as Cd levels decreased, other essential crop growth factors were enhanced remarkably. There is a limitation that did not apply to other crops to evaluate the effect of two NPs [90].

Various synthetic chemicals were tested to protect against the effects of the ShB (*Rhizoctonia solani*) pathogen on rice crops. However, synthetic chemicals are harmful to the environment and other essential bacteria. That is why researchers have extracted biodegradable NPs from Chitosan (*Penaeus monodon*), which is not detrimental to the environment. To complete the research, two types of experiments have been conducted: one under greenhouse conditions and the other by detaching rice leaves. The most prominent result was obtained from detached life compared to greenhouse conditions. It is applied both as a seed and foliar spray on rice plants. Foliar spraying of chitosan nanoparticles has shown better results than seed application, although the experiment was conducted in pots to determine the effects of these newly invented NPs [91].

Table 1. Advantages of nano-sized materials treatment in various rice plant adaptations.(orginal)

Rice variety	Materials	Particles size	Treatment	Medium	Time	Effects	Location	Reference
IRRI-6	ZnO NPs	20-30 nm	0, 5, 10, 25, and 50 ppm concentrations were used as seed priming	Field trial in experiment plots	12 hours in photoperiod exposure	Obtained the capacity to combat both water shortage and irrigated conditions with higher yield	Pakistan	[88]
Hybrid rice Yliang-you 900	CeO_2 NPs	620.73±50.31 nm (solution) in deionized water	200 mgL^{-1} CeO_2 NPs, 50 μM $CdCl_2$, 50 mM NaCl, one week's rice seedlings	Hydroponic	two weeks	Reduced DNA damage, $CdCl_2$, and NaCl stress.	China	[89]
Rice	TiO_2 and SiO_2 NPs		0, 5, 10, 15, and 20 mg/L after one week of transplanting	Foliar spray	One-week intervals	Decreased cadmium accumulation and enhanced antioxidant defense	Multan, Pakistan	[90]
Jyothi	ChNp (Chitosan)		Greenhouse condition 1 mg/mL Both seed and foliar spray.	By brushing the respective solution of the leaf	7 days and room temperature	95% ShB suppressed from the detached leaf	Kerala, India	[91]

Rice variety	Materials	Particles size	Treatment	Medium	Time	Effects	Location	Reference
			pre-soaked seed for 2h and foliar spray 15 days after sowing	surface				
Rice	ZnO NPs	68.1 nm	(1) background As and Cd, (2) Extra adding As and Cd, (3) Extra adding As and Cd with 100 mg Kg^{-1} ZnONPs. (4) ZnONPs 100 mg Kg^{-1} with background soil, (5)100 mg Kg^{-1} Zn^{2+} with extra addition of As and Cd, (6) Adding 100 mg Kg^{-1} Zn^{2+} with Background soil	Soil, Greenhouse conditions	2 days	Reduced As and Cd accumulation in rice tissues together	Taxes	[92]
Giza 178	Nano Zn, Nano SiO_2	nano-Zn (30 nm) or nano-SiO_2 (25 nm)	nano-Zn (30 nm) with 50 mg/L or nano-SiO_2 (25 nm) with 2.5 mg/L	Foliar	Three times, after transplanting 3,5 and 7 weeks	Successfully grown under water-stressed conditions with better yield and other growth parameters	Damietta, Egypt	[85]
Hybrid Rice (EHR1)	SiO_2 NPs	50 nm (Spherical)	90 ppm	Foliar	Irrigation every 9 days	Reduced water stress	Egypt	[87]
Super Kernal	$AgNO_3$, AgNPs and *Aspergillus innoculum*	34 nm	75 mg/L($AgNO_3$ and Ag NPs) Aspergillus was applied after 10 days AgNPs application	Soil application by solution at the heading stage	3 months	Suppressed biotic stress and enhanced rice yield and other antioxidant defense	Chak Qazi Bhera, District Sargodha, Pakistan	[93]
Y900	CeO_2 NPs	520 nm	100 mg/L and 500 mg/L 7 days seedlings	Hydroponic	3 weeks	Improved rice growth and nitrogen assimilation. Reduced oxidative membrane and DNA damage	China	[94]
Kargi CSR 30	ZnO-NPs	< 50 nm	1) Control (without salt stress). 2) under saline water (60 mM NaCl) 3) under saline conditions (80 mM NaCl) 4) under saline conditions (100 mM NaCl) 5) Application of ZnONPs(50 mg/L) +salt stress (60 mM NaCl) 6) Application of ZnONPs(50 mg/L)	Hydroponic	2 weeks	Improved Salt Tolerance in Rice Seedlings	India	[95]

Rice variety	Materials	Particles size	Treatment	Medium	Time	Effects	Location	Reference
			+salt stress (80 mM NaCl) 7) Application of ZnONPs(50mg/L) +salt stress (100 mM NaCl).					
Giza178 Giza177	NPs-Se NPs-Si (SiO_2)	NPs-Se (50–100 nm) NPs-Si (SiO_2) 10 nm	1) control (distilled water) 2) grain soaking in NPs-Si(12.5 MgL^{-1}), grain soaking NPs-Se(6.25 MgL^{-1}) 3) NPs-Si foliar at mid-tillering stage (MT) 4) NPs-Se foliar at MT, NPs-Si foliar at panicle initiation (PI) 5) NPs-Se foliar at PI, NPs-Si foliar at mid-booting stage (BT) 6) NPs-Se foliar at BT	Experimental Farm	2 weeks	Both NPs-Si and NPs-Se positively influenced rice growth and yield as well as mitigated salt stress.	Egypt	[86]
CO39 and Nippon-bare	SiO_2 NPs	average± standard deviation (39± 7 nm)	SiO_2 NPs (10, 100, 500, 1000, 2000, and 3000 mg/L)	Hydrophoic	2-week-old rice seedlings (cv. CO-39) by spraying two hours before inoculation	Stimulate plant immunity to rice against M. *oryzae*	China	[96]

Both cadmium and arsenic are detrimental to humans and other species. If rice is cultivated under Cd and As-contaminated soil, it takes Cd and As into its tissues. Subsequently, it enters consumers' important organs. There are available ENPs (Engineered Nanoparticles) that can reduce either Cd or As. To conclude, the researchers produced ZnO NPs and applied them to rice plants, which showed a significant reduction in Cd and As together. This experiment was carried out under greenhouse conditions with six treatments, but a more appropriate result was obtained with 100 mg kg-1 ZnO NPs, with both background and extra-added As and Cd in theoil [92].

Saline and sodic soils are a major concern for farmers cultivating rice and other crops, especially in the Nil Delta region. To overcome this issue, farmers use conventional practices, such as burning rice or cotton straw on the cultivation land, which increases air pollution and contributes to global warming. To address the major issue, a group of researchers conducted an experiment in which they buried cotton or rice straw in small field ditches and cultivated rice in that field using Zn-NPs or Si NPs at 50 mgL-1 and 2.5 mgL-1, respectively, via foliar spraying. The result of this experiment suggested that the application of Zn NPs on cotton straw fields had a greater impact than rice straw yield with the application of Si-NPs [85].

High water stress is a major concern for rice and other crops in higher-water irrigation regions. As it is a major concern, it reduces the high rice yields every year. EHR1 is a hybrid rice variety cultivated under water regime conditions for 3,6 and 9-day irrigation with foliar applications of Silica nanoparticles with three treatments except control. The application of

SiO_2 NPs demonstrated that it could enhance rice yield attributes and antioxidant defense of rice in both IR6 and IR9. Nevertheless, the most appropriate result was obtained from the application of IR9 in rice with SiO_2 NPs [87].

Biotic stress affects various crops, including rice. Two chemicals have been used to determine the effect of their application on a rice variety named Super Kernal, which are Ag NPs and $AgNO_3$.The AgNPs are produced from a plant extract that is sustainable for the environment. It was applied with different concentrations of $AgNO_3$ and $AgNO_3$ at the heading stage by foliar spray. Both AgNPs and $AgNO_3$ have shown significant results, such as suppression of biotic stress and enhanced rice production. However, the effect of AgNPs was more remarkable than the application of $AgNO_3$ [93].

Nitrogen stress and Nitrogen deficiency in rice land are common in almost every region; for these reasons, rice cannot be adapted to uncomfortable conditions. CeO_2 NPs were used to determine their impact on rice while low or high-concentrated nitrogen was present in the soil. After cerium nanoparticle use under both low and high nitrogen-concentrated soil, it completely balanced and gave higher yield as well as other agronomic profiles [94].

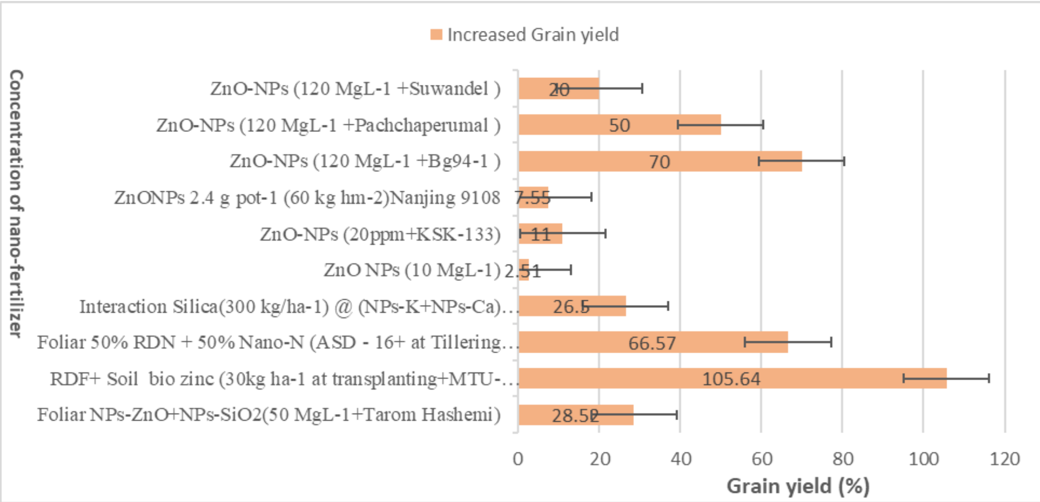
Salinity is a climate issue categorized as abiotic stress that affects crop growth and production, particularly rice. Two types of rice varieties are named Kargi and salt-tolerant CSR30.To determine the effect of ZnO NPs on the two rice cultivars' seeds applied in hydroponic conditions under salinity. It has shown an appropriate result, reducing the salinity stress and increasing the yield growth factors of rice plants. The key result from the ZnO NPs was enhanced photosynthetic pigments and antioxidant parameters in both Kargi and CSR30 under salinity-stressed conditions [95].

Salinity occurs mainly in arid and semi-arid areas, while the water supply system is almost unavailable. However, nanotechnology comes up with great solutions such as nanomaterials, including Si-NPs and Se-NPs. The applications of silicon and selenium nanoparticles have shown remarkable success in improving the salt tolerance of the rice variety Giza 177, both at the BT stage via soaking and foliar spraying. Applications of Si-NPs and Se-NPs on rice improved the water content of plants and leaf area. It has resulted in high rice yield and healthy rice under salinity [86]. Biotic and abiotic stresses are the issues faced by many farmers while growing some crops under drought and other climate-related diseases. Silica nanoparticles are a weapon that helps to struggle against the issues by triggering antioxidant levels; as a result, they help to cultivate a better crop, particularly rice, under these issues. In addition, SiO_2 NPs are also helpful for root development, which promotes rice adaptation against drought stress through their foliar application on rice. Furthermore, it is effective for working against the blast fungus of rice caused by *Magnaporthe oryzae*. However, SiO_2 NPs were not used for other crops except rice [96].

SeNPs improve the rice seeds' germination and strengthen their antioxidants while combating oxidative stress. In this study, some treatments were applied during the germination state of the seed. However, soaking rice seeds with 0.5 mg L-1 SeNPs ameliorates the activity of key enzymes involved in rice growth and stress tolerance. Therefore, the findings indicate that SeNPs could enhance antioxidant defenses by aiding crop fortification and sustainable agriculture [97]. Bacterial leaf blight and sheath blight diseases are vulnerable to rice crops. Traditional strategies cannot suppress the disease with the desired view. Hence, the nanotechnology-assisted particles need to be implemented. In this study, scientists used two nanoparticles, CuNPs and AgNPs. Nanocomposite of these two NPs has shown improved stability and efficacy against the *Xanthomonas oryzae pv. Oryzae* and *Rhizoctonia solani*.After all, copper and silver nano-composites are effective against the devastating rice disease [98]. In recent years, biosynthesized nanoparticles have played a vital role due to their environmental friendliness and economic benefits. This study was conducted to investigate the effects of biosynthesized (ethanol crude) ZnO NPs on rice plants. The biosynthesized ZnO NPs showcased essential suppression of *X. oryzae pv. oryzae* growth, demonstrating an in vitro 50% inhibitory concentration (IC_{50}) range of 1.895 mgL^{-1} and a minimum inhibitory concentration (MIC) range of 4 mgL^{-1} [99].

5. Nano-Fertilizer Helps to Improve Rice Plant Growth

The bar chart demonstrates increased grain yield by using nano fertilizer on various rice varieties with different concentrations. Applying ZnO-NPs (120 mgL^{-1}) on different rice varieties, Suwandel, Pachchaperumal, and BG94-1, has increased grain yield of 20%,50%, and 70%, respectively [100]. On the other hand, ZnO-NPs 60 $Kghm^{-2}$ on Nanjing 9108, ZnO-NPs 20 ppm on KSK-133, and 10 mgL^{-1} on rice have enhanced 7.5%, 11%, and 2.51%, respectively [101–103]. Furthermore, interacting with silica-NPs on Anber33, foliar spraying (50% RDN, 50% Nano-N) on ASD-16, RDF+Bio-Zinc (30 kgh^{-1}) on MTU-1010, and foliar spraying with ZnO-NPs on Tarom Hashemi rice variety have augmented grain yield 26.5%, 66.57%, 105.64% and 28.52%, respectively, as compared to the control [104–107].



Graph 2. Improved rice grain yield by using different concentrations of nano fertilizer.

Nano fertilizer has shown efficacy on rice plants due to its small size, reduced target wastage, and nutrient use efficiency. There is a study where ZnO-NPs were applied as the foliar application of nano ZnO (50-500 nm) fertilizer on three rice varieties, inbred (Bg94-1) and traditional (Pachchaperumal, Suwandel) in Srilanka. Four treatments have been implemented, including bulk ZnO 60 mg/L, distilled water, nano-ZnO 60 mg/L, and nano-ZnO 120 mg/L under hydroponic conditions. The most suitable result was obtained from nano ZnO 120 mg/L foliar application on the Bg94-1 cultivar. The other two varieties (Pachchaperumal, Suwandel) have also given almost similar results, such as high-yield performance[100]. Zn deficiency is a major concern for rice because it'san essential micronutrient for both plants and humans. To ensure Zn availability for rice crops, research has been conducted by applying nano ZnO with foliar and soil ($ZnSO_4.7H_2O$) in rice (MTU-1010) in both dry and wet seasons. Soil 5 kg/ha $ZnSO_4.7H_2O$ and nano ZnO 0.30% by foliar spray was used as a treatment in one of the Indian research institutes in West Bengal. The application of 0.30% foliar spray at the flowering and post-flowering stage has shown a magical improvement of leaf chlorophyll, Zn content, plant height, and quality of rice compared to soil 5 kgha^{-1} $ZnSO_4.7H_2O$ [108].

Table 2. Effects of nanomaterials on different varieties of rice plants.

Rice variety	Materials	Particle size	Treatments	Application	Time	Effect	Location	Reference
(Pachchap erumal, Suwandel) and inbred (Bg94-1)	nano-ZnO	from 50 nm to 500 nm	1. Control (distilled water) 2. bulk ZnO 60 mg L-1 3. nano-ZnO 60 mg L^{-1} (Conc. 1) 4. nano-ZnO 120 mg L^{-1} (Conc. 2)	foliar	Two times, 40 days after sowing and 70 days filling stage of grains	All the nano-Zn effects were almost similar, but the 120 mg/L application on Suwandel was most effective.	Sri Lanka	[100]
MTU-1010	foliar Nano-ZnO and soil $ZnSO_4.7H_2O$	(1-100) nm	1.(Control) 2. Zn @ 5 kg Zn/ha as $ZnSO_4.7H_2O$ (Basal) 3. Zn as $ZnSO_4.7H_2O$ at 25 DAT 4. Zn as $ZnSO_4.7H_2O$ at Flowering 5.Zn as $ZnSO_4.7H_2O$, half dose as basal + half dose at 25 DAT 6.Zn as $ZnSO_4.7H_2O$, half dose as basal + half dose at Flowering 7.Zn as $ZnSO_4.7H_2O$, half dose at 25 DAT + half dose at Flowering 8.0.03% Nano-ZnO spray at the time of flowering and post-flowering	Soil and Foliar	Three times after transplanting (15 days, 30 days, 45 days)	Foliar spraying (0.30%) increased leaf Zn concentration, chlorophyll content, plant height, and quality of rice grain compared to the soil Zn 7 application.	West Bengal, India	[108]
Bg360, BW364, Kaluheena ti, and Kuruluthu da.	Nano-CuO, Nano-ZnO	Nano-CuO 26 nm, Nano-ZnO 31 nm	1. (distilled water) 2.30 mg L^{-1} 3. 60 mg L^{-1} 4. 120 mg L^{-1} With Nano-CuO, Nano-ZnO, and Nano-ZnO-CuO	Foliar Spraying	at 48-58 days after sowing (DAS) and grain filling stage 100-105(DAS)	All the particle attributes significantly improved	Sri Lanka	[18]
ASD – 16 (110 days)	Nano Urea	20-50 nm	1. Control 2.100% Nano N 3. 90% RDN + 10% Nano N 4. 80% RDN + 20% Nano N 5. 70% RDN + 30% Nano N 6. 60% RDN + 40% RDN 7.50% RDN + 50% Nano N 8. 40% RDN + 60% Nano N.	Foliar spray	Two split doses (Tillering and Panicle initiation stage).	The highest growth attributes and yield attributes found in T7	Tamil Nadu, India	[107]
Anber 33	Silica Fertilizer and Spraying with Nano-Potassium	(1-100) nm	silica fertilizer 0, 100, 200 and 300 kg ha-1 and spraying nano fertilizers control, nano-K, nano-Ca, nano-(K + Ca)	Fertilization and spraying	every 3 days) starting from the irrigation of germination until the patching phase	Increased yield and growth of crops. Reduced the amount of fertilizer and reduced the waste of fertilizers	Governor ate/ Iraq	[104]

Rice variety	Materials	Particle size	Treatments	Application	Time	Effect	Location	Reference
Rice	Nano-silicon	(1-100) nm	T1: Control T2: 100% NPK & 100% Zinc application (RDF) T3: 50% N; 100% P & K + 2 spray of Nano Nitrogen T4: 0% Zn, 100% NPK + 2 spray of Nano Zinc T5: 50% N & 0% Zn; 100% P & K + 2 spray of Nano N mixed with Nano Zn and T6: 50% N & 0% Zn	Foliar	Regular monthly intervals	In the T6 treatment, the yield performance was higher than in other treatments	Kumarganj, Ayodhya (U.P.)	[109]
Cultivar Super	Mesoporous $ZnAl_2Si_1{}^0O_{24}$ nano fertilizers	55.2 nm	1. (control) 2. 30 mg kg^{-1} 3.60 $mgkg^{-1}$ 4.90 $mgkg^{-1}$ 5.120 $mgkg^{-1}$ 6.150 $mgkg^{-1}$ Of Nitrogen	Pot experiment	1 time applied urea nanocomposite	Slowly released and with time augmentation, the release decreased	Pakistan	[110]
PR-121	ZnONPs	50 nm	0, 0.5, 1.0, and 5.0 g L^{-1}	pot study	15-day interval	The highest values were obtained at 1.0 g L^{-1} ZnONPs application	Ludhiana, Punjab, India	[111]
MTU-1010	Nano Zinc	(1-100) nm	T1. Control T2- RDF @ N, P_2O_5, K_2O @ 120:60:40 kg ha^{-1} T3-RDF+Soil application of $ZnSO_4$ @ 25kgha-1 at transplanting T4 RDF +Soil application of nano Zn @ 10 kg ha-1 T5- RDF +Soil application of nano Zn @ 15 kg ha-1 T6 RDF +Soil application of bio Zn @ 15 kg ha-1 T7- RDF +Soil application of bio Zn @ 30 kg ha-1 at transplanting T8-RDF +foliar application of 0.2 % as ZnSO4 at tillering and panicle emergence stage, T9 and T10-RDF +foliar application of 1 mL l-1 and 2 mL l-1 as nano zinc at tillering and panicle emergence stage, T11 and T12 -RDF +foliar application of 1.5mL l-1 and 3mL l-1	soil and foliar	2 weeks	grain (5355 kg ha-1), straw yield (6347 kg ha-1) was recorded highest in the treatment receiving RDF+ Soil application of bio zinc @30 kg ha-1	Rajendranagar, Hyderabad	[105]
Nanjing 9108	ZnO nanoparticle	20–50 nm	T1, T2, T3, T4, and T5 treatments with 7.5, 15, 30, 60, and 120 kg hm^{-2}	Soil	3 times	ZnO NPs increased rice yield by 2.5% to 11.8% compared to the control	Jiangsu Province, China	[101]

Rice variety	Materials	Particle size	Treatments	Application	Time	Effect	Location	Reference
Tarom Hashem	SiO_2 NPs, ZnO NPs	SiO_2(20 -30 nm) ZnO (10-30nm)	T1. Control T2. Soil application of calcium silicate T3, Soil application of zinc sulfate T4. Soil application of calcium silicate + zinc sulfate T5. Foliar application of nano-SiO_2 T6 Foliar application of nano-SiO_2 + soil application of calcium silicate T7. Foliar application of nano-SiO_2 + soil application of zinc sulfate T8. Foliar application of nano-SiO_2 + soil application of calcium silicate + zinc sulfate T9. Foliar application of nano-ZnO T10. Foliar application of nano-ZnO + soil application of calcium silicate T11. Foliar application of nano-ZnO + soil application of zinc sulfate T12. Foliar application of nano-ZnO + soil application of calcium silicate + zinc sulfate T13. Foliar application of nano-SiO_2 + nano-ZnO T14. Foliar application of nano-SiO2 + nano-ZnO, soil application of calcium silicate T15. Foliar application of nano-SiO_2 + nano-ZnO + soil application of zinc sulfate T16. Foliar application of nano-SiO_2 + nano-ZnO + soil application of calcium silicate + zinc sulfate	Soil and foliar	after a week of transplanting	The highest grain yield (4502 kg ha-1) gained by the application of T13 (nano-SiO_2 + nano-ZnO)	Noor Region of Iran	[106]
Rice	Biogenic ZnO NPs	14.95 nm	1.Ta (distilled water) control 2. Tb ZnO (5 mg/L) 3. Tc ZnO (10 mg/L) 4. Td ZnO (25 mg/L) 5. Te ZnO (50 mg/L) 6. Tf ZnO (100 mg/L) 7. Tg ZnO (200 mg/L)	Foliar	14 hours with seed	ZnO nanoparticles at 10 mg/L improved seed germination (100%), leaf length 33.0 mm), and leaf width (2.0 mm) with other factors.	Tamil Nadu, India	[103]
hybrid variety KSK-133	ZnO nanoparticles	20 nm	T1.Control (without Zn) T2. NZnFS (nano Zn foliar spray at the rate of 20 ppm suspension of ZnO) T3. NZnSA (nano Zn	Foliar spray, soil application	2 weeks before panicle initiation	ZnO NPs increased fresh biomass, grain yield, and Zn content in grain and straw as compared to the control. Soil application of ZnO	Pakistan	[102]

Rice variety	Materials	Particle size	Treatments	Application	Time	Effect	Location	Reference
			soil application at the rate of 4 ppm of ZnO) T4.NZnRD (nano Zn root dipping at the rate of 2% solution of ZnO) T5.BZnFS (bulk Zn foliar spray at the rate of 20ppm suspension of ZnO) T6. BZnSA (bulk Zn soil application at the rate of 4ppm of ZnO) and BZnRD (bulk Zn root dipping at the rate of 2% solution of ZnO).			NPs also increased husk and root zinc by 21% and 29%		

Rice production has decreased due to the growing population, the limitation of land, and various climate changes. To meet the increasing demand, researchers proposed to use nanotechnology for the assessment of the yield performance of nano-CuO and nano-ZnO micronutrient fertilizers applied with three treatments: nano-CuO 60 mg L^{-1} (T1), nano-ZnO 30 mg L^{-1} (T2), and nano-CuO-ZnO composite 120 mg L^{-1} (T3). This nano fertilizer has been applied after 48 -58 days of sowing and 100-105 days in the filling stage. The significant increase was demonstrated with the application of non-fertilizer CuO and ZnO, and the growth parameters of rice plants increased in specific rice varieties Bg360, BW364, Kalu Heenati, and Kuruluthuda. It was mentioned that nano-CuO, nano-ZnO, and nano-CuO-ZnO increased the grain yield of Bg360, BW364, Kalu Heenati, and Kuruluthuda rice cultivars [18].

Urea is a key element for rice growth, especially for the farmer. However, a wide range of urea usage causes harmful impacts on the environment. That is why nano-urea can be a great choice for current rice cultivation, aiming for high rice yields and reduced environmental impact. Here is a piece of field study to investigate the nano-urea for rice (*Oryza sativa*).In this study, a total of eight treatments were implemented by foliar spray on the rice variety of ASD – 16 on the tillering and panicle initiation stage. However, the most significant result was found from the application (50% RDN + 50% Nano-N) by foliar application, where the Grain yield was 7056 kg ha^{-1} and the number of tillers was 348 [107].

Silica fertilizer can help rice growth and its other essential rice growth factors. To determine the integrated effect of silica fertilizer and nano-K and nano-Ca on Anber33-named rice plants. Sixteen treatments were used with three replications. After silica fertilization of 300 kg ha^{-1}, the harvest index became 30.96%. However, after foliar application of the mixture of nano-k (27%) and nano-Ca (7%) before the flowering stage, the harvest index became 32% [104].

The rapid release of urea and Zn is a significant environmental concern, along with limited yields for many crops, particularly rice. To tackle these issues, slow-release fertilizers are most important for achieving a good rice yield. In this study, a mesoporous nanocomposite loaded with urea and Zn, synthesized from rice husk, was used; it is green and environmentally supportive. After using this nanocomposite in rice fields, yield increased compared to urea alone because of its slow-release Nitrogen and Zinc [110].

Zn is an essential element for humans, plants, and animals. To focus on Zn deficiency in rice, a pot experiment was conducted on the PR121 rice variety in Zn-deficient soil using foliar-applied ZnO nanoparticles as a fertilizer, with four treatments, including a control.

Nevertheless, the most prominent result was obtained from the application of 5 gL^{-1} of foliar spray, whereas only root growth factors improved from 1 gL^{-1} foliar spray of ZnO NPs at 15-day intervals of rice. The main finding of this experiment, the result of the study, was concentration-dependent [111].

Here is another piece of work on the rice variety of MTU-1010, where nano-Zn was used in both soil and foliar application. Both soil and foliar applications have shown significant impacts on rice yield and on enhanced nutrient content and uptake. On the other hand, the highest outcome was found from RDF + bio-Zn by soil application and the grain yield obtained (5355 kg ha^{-1}) [105].

ZnO-NPs are the most significant and widely used element because they are used for humans, animals, and plants. Herein, a pot experiment was carried out to determine the effects of the utilization of ZnO-NPs for rice plants as a fertilizer. The application consists of five doses of Zn (0.3, 0.6, 1.2, 2.4, and 4.8 g Zn pot^{-1}). All the dogs have given better results, including high rice yield and growth contents, except for those without ZnO NPs.It could be a great fertilizer for future usage to obtain smart results, especially for rice plants [101].

Silicon is the most essential element for plants after Zn and N, especially for rice crops. It is also important to control heavy metals such as Cd, As, and Pb for rice and other crops. A field study was conducted in the Noor Region of Iran, applying 16 treatments with 3 replicates to evaluate the combination of Silicon and Zinc nanoparticle foliar spraying. The results were notably better when NPs were applied by foliar spray, but there were no greater differencewhen nano fertilizer was used [106].

Sustainable agriculture plays an important role in keeping the environment fresh and sound. To focus on that concern, researchers have extracted a biogenic nanoparticle from seaweed (*Turbinaria ornate*) and applied it to rice seed as a foliar application of 10 mgL^{-1} to make nano-primed rice seed. The nano-primed rice has an augmented germination rate of 100%, grain weight (653 g/ m^2), leaf area, and other essential antioxidants for saving the environment [103].

Another pot experiment on Zinc nanoparticles was carried out in Pakistan, where ZnO NPs were prepared by a cost-effective co-precipitation approach. In this study, ZnO NPs were applied to plants using foliar, soil, and root-dipping methods, as plants are more Zinc-sensitive in the roots and leaves. Overall, the best result was found from the foliar application of the ZnO NPs on rice plants [102].

The effect of DAF fertilizer and nano fertilizer has been determined on rice(Anber 33) by using spraying. The application was organized by two factors, such as DAP and Nano fertilizer. The rice plant was treated with DAP fertilizer using Control-DAP, O-DAP+ micronutrients, and O-DAP high K. On the other hand, Nano fertilizer was treated by Control, Nano silicon, Nano complete, and Nano silicon + Nano complete with the spray. The researcher clearly described that they got higher results using non-fertilizer than DAP fertilizer. Especially, plant height (cm), leaves (SPAD unit), biological yield (ton h^{-1}), harvest index (%), and grain yield (ton h^{-1}) have significantly improved. It indicates a brighter glimpse of the utilization of nano fertilizer in agricultural applications [112].

Biosynthesized $ZnMgO_2$ (bimetallic oxide) nanoparticles have been used as nanofertilizers for rice plants. The nano fertilizer is sustainable for the environment and cost-effective because it is extracted from the plant leaf *Cinchona succirubra (C. succirubra*). Significant rice growth and antioxidant performance were observed from the concentration of

$ZnMgO_2$ NPs 25 mgL^{-1} and 75 mgL^{-1}.The NPs also show the standard size range, which is 23 nm. This is the focal point that helps to take the plant the NPs into their body.

6. Limitations of Nanotechnology and Its Environmental Effects

Nanotechnology has shown its power in various fields, including agriculture and so on. However, it is essential to consider its limitations and negative environmental effects. One of the primary concerns connected with nanotechnology is the toxicity of nanoparticles. While nanomaterials offer unique properties and functionalities, their interactions with living organisms and ecosystems remain poorly understood. It is important to thoroughly investigate the adverse effects of nanoparticles on human health, wildlife, and the environment [113]. Furthermore, the scalability and cost-effectiveness of nanotechnology applications in agriculture pose challenges. The production of nanomaterials at a wide range can be technically complex and economically burdensome. The cost of production, as well as the accessibility and affordability of nanotechnology-based solutions, may reduce their widespread adoption, especially in resource-constrained agricultural settings [114]. Another concern is that nanomaterials' significant environmental impact, due to their unique properties, may cause them to behave differently in the environment than their bulk counterparts. The release of nanomaterials into soil, water bodies, and the atmosphere raises questions about their long-term fate and transport, as well as their potentialo accumulate in living organisms [115]. The effectiveness of nanoparticles in entering food chains and ecosystem compartments necessitates a widespread understanding of their persistence, mobility, and adverse effects on non-target organisms and ecological processes [116].

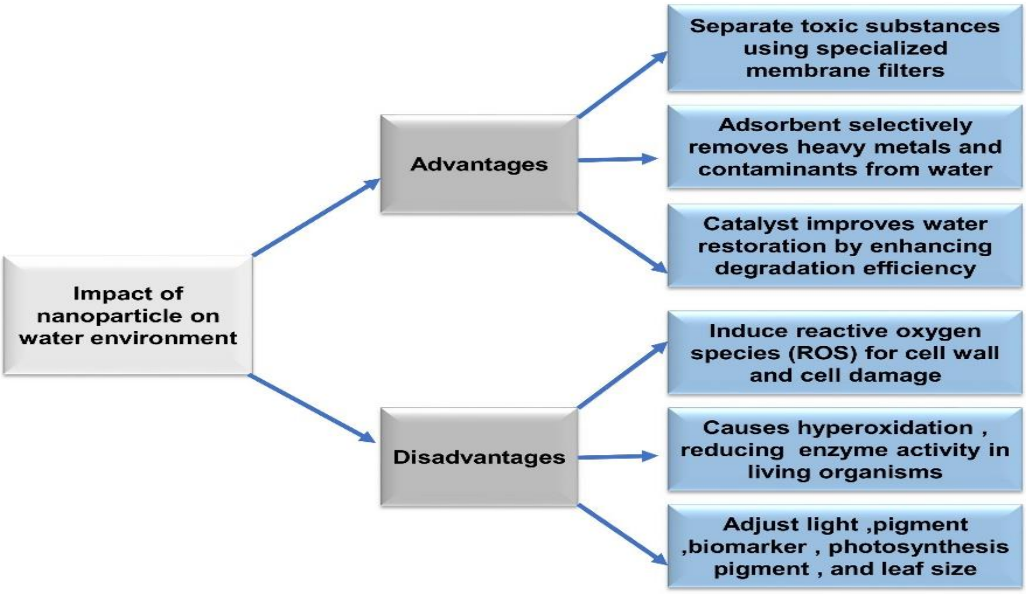


Figure 3. Pros and Cons of nanoparticles in the aquatic environment.

In addition, the disposal and management of nanomaterial-containing waste products are critical considerations when they are emitted into the environment. The growing use of nanotechnology across industries, including agriculture, raises concerns about the release of nanomaterials into the environment via waste systems. Proper waste management strategies need to be implemented to reduce the unintended release and accumulation of nanoparticles, ensuring their safe disposal and minimizing risks to ecosystems and human health [117].

Furthermore, the important framework for nanotechnology in agriculture needs attention. As nanotechnology advances, the development of appropriate regulations and guidelines becomes paramount. Effective strategies and standards should be established to ensure the safe and responsible use of nanomaterials in agricultural applications, addressing concerns regarding safety, labeling, and risk assessment [118]. It is important to establish comprehensive risk assessment protocols to assess the environmental impacts of nanomaterials at every stage, from production to disposal.

Despite having these limitations and challenges, ongoing research is focused on addressing the environmental effects of nanotechnology and developing its sustainability. Scientists tend to investigate the ecotoxicological effects of nanomaterials, seeking to understand their interactions with organisms and ecosystems and identifying techniques to reduce their risks [119]. Sustainable production strategies for nanomaterials, for example, green synthesis approaches, are being explored to reduce the environmental impact of nanotechnology [120]. Furthermore, life-cycle assessments and techno-economic analyses are being conducted to assess the overall sustainability and environmental performance of nanotechnology-based agricultural applications [121].

Therefore, while nanotechnology offers promising strategies for agricultural advancement, it is essential to consider its limitations and environmental impacts. The potential toxicity of nanoparticles, cost-effectiveness, scalability, environmental impact, waste management, and regulatory challenges must be carefully addressed. Ongoing research intent and multidisciplinary collaboration are vital for understanding and minimizing potential risks, including those associated with nanotechnology, ensuring its safe and sustainable implementation in agriculture and other fields.

7. Future of Nanotechnology and its Environmental Effects

Nanotechnology has emerged as a promising frontier in agriculture by offering potential solutions to improve crop productivity and adaptability. To appropriate rice cultivation, nanotechnology holds substantial promise for enhancing yield growth and adaptation to changing environmental conditions. Nanofertilizers are among the key nanotechnological interventions that use nanoparticles associated with essential nutrients. These nano fertilizers have been proven to improve nutrient uptake, enhance nutrient use efficiency, and promote rice plant growth. For example, nanoscale silicon (Si) and nitrogen (N) formulations have shown increased rice yields [122]. Nanopesticides are another application of nanotechnology and have the potential to revolutionize pest and disease management in rice and other crops. By implementation, nanoencapsulation strategies and nano pesticides can be targeted for precise delivery, controlled release [123–126], and increased ability. This method offers the advantage of reducing the number of agrochemicals needed while improving pest control efficacy[54].

In addition, nanosensors can detect and monitor various parameters in real time, including soil moisture, nutrient levels, and plant physiological responses. By ensuring accurate, timely data, nanosensors can enable precise irrigation and nutrient management in rice fields, leading to improved water and fertilizer use efficiency [127]. The integration of nanosensors in rice cultivation methods allows farmers to improve resource allocation and promote optimal growth conditions for the crops. Nanomaterials, such as nanoparticles and nanocomposites, exhibit unique properties that can be leveraged to enhance stress tolerance in rice plants. These materials can eliminate reactive oxygen species, regulate hormone levels, and reduce the adverse effects of abiotic stresses, including salinity, drought, and heavy metal toxicity [69]. By incorporating nanomaterials, researchers aim to improve rice crop resilience to challenging environmental conditions, ensuring consistent and sustainable yields.

The application of nanotechnology in rice cultivation and rice improvement has demonstrated promising effects on yield growth and adaptation strategies. The improved nutrient availability provided by nano fertilizers enhances ice yields and crop productivity [122]. Nanopesticides have demonstrated pest control effectiveness and reduced yield losses caused by pests and diseases. The targeted delivery and controlled release of active components ensure optimal protection of rice crops [54]. The utilization of nanosensors supports precision agriculture and enables farmers to monitor soil conditions, plant health, and environmental parameters in real time. These data-driven approaches facilitate timely interventions and improve resource management, ultimately increasing rice yield and improving resource utilization [127]. Nanomaterials have demonstrated promise in increasing stress tolerance in rice plants, enabling them to withstand challenging environmental conditions and maintain yield under abiotic stressors [69]. Nanomaterials enhance the adaptability of rice crops in dynamic environmental conditions by modulating plant responses and alleviating stress-induced damage.

Several challenges and considerations need to be addressed, while the future of nanotechnology in rice agriculture appears promising. The long-term effects of nanomaterials on soil health and ecosystem sustainability must be thoroughly investigated regarding nanoparticle toxicity and potential environmental impacts [122]. Furthermore, cost-effectiveness and scalability are important factors to confirm the practical implementation of nanotechnological interventions in rice cultivation methods. Proper standardization of protocols and guidelines for the safe and efficient use of nanotechnology in agricultural practices is important for widespread adoption [122]. To ensure the safe and responsible implementation of nanotechnology in rice agriculture, future research should focus on developing environmentally friendly and sustainable nanomaterials, advancing the understanding of the interactions between nanomaterials and plants, and conducting widespread risk assessments.

After all, nanotechnology presents exciting possibilities for enhancing rice yield growth, adaptation, and so on. Nanofertilizers, nanosensors, nanopesticides, and nanomaterials offer innovative strategies to address the challenges in rice cultivation, including nutrient management, pest and disease control, resource utilization, and stress tolerance. The integration of nanotechnology into rice agriculture has the power to revolutionize farming practices and improve productivity, thereby contributing to sustainable, resilient rice production systems.

8. Conclusions

Nanotechnology has been a significant change agent in agriculture, with interventions to improve rice yields and sustain farming practices amid the challenges posed by escalating climate change. Therefore, leveraging the unique properties of nanofertilizers and nanoparticles, this technology increases nutrient efficiency, further enhancing the rice plant's resilience against abiotic stresses such as drought, salinity, cold, heat, and heavy metal toxicity, resulting in increased grain yields. Nanofertilizer increased environmental sustainability by reducing nutrient losses, preventing soil nitrogen imbalances, and lowering greenhouse gas emissions. However, challenges on the production cost side, concerns about nanotoxicity, and strong regulatory frameworks need to be addressed to make it safe for widespread adoption worldwide. Research continuity, investment, and global collaboration will play an imperative role in developing nanofertilizers that serve their purpose and gain public acceptance. Once all these hurdles are surmounted, nanotechnology will be a revolutionary force in agricultural systems, advancing food security and environmental conservation for future generations. In conclusion, the rise in nano fertilizers brings several benefits. It is a viable asset for adapting rice plants to climate change effects, mitigating agriculture's contributions to those effects, and advancing sustainable agriculture.

Author Contributions

Conceptualization, J.S. and A.M.B.; resources, J.S. and A.M.B.; data curation, A.M.B.; writing—original draft preparation, J.S.; writing—review and editing, A.M.B.; visualization, J.S.; supervision, A.M.B. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

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