



Enhancing the Growth of Rice (*Oryza sativa*) in a Hydroponic System Under Nutrient Stress

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Rice (*Oryza sativa*), a food mainstay for over half of the world's population, faces substantial production challenges stemming from nutrient deficits, water constraint, and the impacts of climate change. Traditional soil-based systems are generally unable to offer appropriate macro- and micronutrients, consequently restricting crop output. Because hydroponics allows for exact nutrient management to maximise rice growth under controlled conditions, it emerges as a sustainable, soil-less alternative. The morphological, physiological, and biochemical adaptive strategies rice plants use to deal with nutritional stress are also described. Further, it shows the significance of root architectural alterations, symbiotic microbial relationships, and the involvement of acid phosphatase and anthocyanin accumulation under stress situations. The hydroponic approach boosts nutrient uptake efficiency, minimises environmental effect, and offers viable solutions for urban and land-limited farming. Although restrictions such as expensive initial investment and the need for technical expertise exist, hydroponics represents a forward-looking option to boost rice yield and promote the development of climate-resilient, nutrient-efficient cultivars capable of satisfying global food demands.

Introduction

Rice (*Oryza sativa*) is the most widely consumed food crop in Asia, serving as a staple for approximately 50% of the global population and about 34.5% of the Indian population. Globally, around 500 to 700 million tonnes of paddy rice are produced and consumed annually. Based on the availability of soil water, rice is grown in a variety of ecosystems, such as deepwater environments, rainfed lowland, rainfed upland, irrigated lowland, and irrigated upland. Roughly 75% of the world's rice is grown in flooded transplanting systems, with direct seeding accounting for the remaining 25%. However, transplanted rice systems face several key issues, such as water scarcity, deficiencies in macro- and micronutrients, methane emissions contributing to greenhouse gases, and various biotic and abiotic stresses, all of which significantly impair productivity. A significant agricultural problem is increasing rice productivity in the face of climate change and fast population increase. Sixteen basic nutrients are needed for rice, with nitrogen (N), phosphorus (P), and potassium (K) being the main macronutrients that are crucial for plant growth, yield, physiological development, metabolic activities, and stress tolerance. However, a major obstacle to reaching ideal yields is limited nutrient availability in soils, which is frequently caused by the fixation of nutrients by inorganic and mineral compounds. Hydroponics, a soil-less farming method, is becoming a viable way to get around these restrictions. Hydroponics ensures improved nutrient availability and uptake by growing rice plants in a balanced nutrient solution specific to each growth stage. This technique not only improves nutrient use efficiency but also makes it possible to create rice types that are both nutrient-efficient and climate-resilient. So providing a viable strategy for long-term productivity in the face of environmental difficulties.

Rice cultivation in hydroponic: A sustainable approach

Conventional puddled transplanted rice farming uses a lot of resources and contributes significantly to greenhouse gas emissions. In this context, hydroponics a soil-less, nutrient solution based farming technique offers a sustainable and efficient alternative for rice cultivation. Although hydroponics has gained popularity in agriculture around the world, its use in India is still restricted because to the high initial investment prices, technical complexity, and farmers' ignorance. Introduced in India in 1946 by W.J. Shalto Douglas and further explored during the 1960s and 70s, hydroponics is still evolving within Indian agriculture. However, the potential of rice hydroponics is great. It allows precise management of water, nutrients, and environmental factors, resulting in enhanced nutrient usage efficiency, reduced pest and disease incidence, and higher yields. Moreover, hydroponics aids climate-resilient agriculture by minimising the carbon footprint, lowering land use, and enabling urban and vertical farming in land-scarce places. Its emphasis on sustainability and resource recycling is consistent with the circular economy's tenets. Research is ongoing to adapt traditional rice types to hydroponic systems by replicating submerged conditions and optimising root development under varying nutrient regimes. Despite existing limitations, rice hydroponics holds promise for transforming Indian agriculture by blending contemporary technology with sustainable techniques. It provides a workable way to boost rice output, guarantee food and nutritional security, and adjust to changing agricultural needs in the face of environmental stress. Hydroponics has the potential to revolutionise rice production in India and open the door to a resilient, high-yielding, and resource-efficient future with the correct legislative backing, technology advancements, and farmer education.

Essential nutrient function in rice physiology and symptoms of insufficiency

Nutrients are required for optimal plant growth and development. Every nutrient have their own character and engaged distinct metabolic and enzymatic activities to regulate plant life cycle. Nutrient deficiencies can result in necrosis, chlorosis, and stunted growth, all of which can lead to large crop losses. Nutrient influence tolerance to crop against different Pest, diseases and pathogen.

Nitrogen: Nitrogen, which is also included in amino acids, proteins, nucleic acids, and chlorophyll, is the primary component of soil organic matter required for rice growth and optimal production. Photosynthesis is a crucial component in increasing rice production. Rice absorbs a lot of photosynthesis at the leaf level, which increases growth, yield, tillering, grain filling, and protein synthesis. It has the highest photosynthetic nitrogen utilisation efficiency (NUE) of any C3 plant. In the absence of nitrogen, rice leaves become short and upright with a leemony yellow colour, turning pale green and chlorotic at the tips, and the tiller shrinks.

Phosphorus: Additionally, phosphorus is a necessary nutrient for a variety of physiological and metabolic processes, including energy metabolism, cell division, DNA synthesis, and phospholipid production as phosphate (Pi) or pi esters. It is in charge of rice's early blooming and root ripening tolerances to various biotic and abiotic stresses. Phosphorous usage efficiency (PUE) in rice only 25% and display obvious symptoms when experiencing phosphorous deficiency as stunted growth, reduced tillering, narrow and short dark green leaves, fewer panicles and grains, and thin stems. Additionally, delays the flowering and maturity by one week to 20 days. Under extreme circumstances, plants may not flower at all, or if they do, a lot of low-quality, empty grains are produced.

Potassium: Potassium is one of the most important elements for rice farming, second only to nitrogen. It has a key role in boosting vascular bundle lignification under flooding conditions, enhancing plant Vigour, stimulating cell proliferation, and buffering organic acids. Additionally, potassium is linked to the lignification of sclerenchyma cells, which enhances lodging resistance. Chlorosis, which is characterised by orange or yellowing leaves, especially at the margins of lower leaves, and stunted growth are signs of deficiency. A

shortage of potassium leads to smaller, lighter rice grains and ultimately results in severe production reduction.

Iron: Iron (Fe) play a critical part in rice photosynthesis. additionally a part of different enzymes, such as dipeptides, catalases, and cytochromes. Due of their immobility, seedlings exhibit deficiency symptoms in their early stages. The initiation of Fe insufficiency is detected with interveinal yellowing and chlorosis of developing plants. A consistent pale-yellow hue with bleached appearances is a result of the progression of Fe insufficiency.

Boron: Boron is necessary for the production of new meristematic cells and plays a critical role in flower creation, pollen germination, and cation absorption. It is essential for the manufacture of cell walls and the preservation of cell membrane integrity. A deficiency in boron often leads to poor pollen viability, negatively affecting reproductive success

Zinc: Zinc is one of the intragal rice micronutrients found in Zn^{++} , $ZnCl^{+}$, and ZnO . Zinc is a cofactor for enzymes involved in N metabolism, such as glutamate dehydrogenase and alcohol dehydrogenase. A zinc shortage substantially lowered ability of rice seedlings to withstand anaerobic soil conditions, decreases anaerobic root metabolism, and inhibits alcohol dehydrogenase function. Zinc deficiency is most likely to affect rice plants in their early growth phases. Crops may also be impacted throughout the reproductive growth stage if the shortfall is not addressed. The earliest phases of zinc deficit in the youngest plants are characterised by chlorotic leaf bases because zinc is not particularly mobile throughout the plant.

Adaptive mechanism exhibits in rice under nutrient deficiency

Rice plants undergo diverse morphological, physiological, biochemical, and rhizosphere mediated alteration to increase nutrient absorption under nutrient deprivation. morphological alterations that promote lateral root, shoot branching, and leaf senescence via altering root architecture. Also associated with different bacteria and fungi to promote nutrient uptake. Rice plant may boost the expression of different nutrient transporter that serve to increase acid phosphatase activity and promote organic acid secretion. Plants attempt to preserve cellular Pi equilibrium in the cytoplasm under phosphorus stress, and they also enhance anthocyanin synthesis.

Morphological response

Root Morphology: The main point of contact between a plant and the earth is its roots. The growth and development of its aboveground components is intimately linked to its morphology and physiology. Achieving high panicle number, spikelets per panicle, grain-filling percentage, and grain yield requires strong root biomass and root oxidation activity.

Root Architecture: In nutrient-deficient conditions, altering root architecture is a crucial tactic to increase NUE. Other root architecture adaptation mechanisms include increased adventurous root, shallower axil root growth angle, horizontal basal root growth, and increased lateral root formation, all of which lead to longer axial roots.

Rhizosphere microorganisms and symbiotic relationship:

One of the most crucial adaptive techniques to improve nutrient acquisition efficiency under stress conditions is symbiotic contact with rhizosphere microorganisms. Arbuscular mycorrhizal fungus (AME) play a vital role in enhancing PAE in growing plant on P deficient soil. Under P deficiency situation AME colonise plant roots to get energy and encourages the formation of roots by lengthening and multiplying root biomass and lateral roots.

Biochemical and physiological responses

a) **Anthocyanin accumulation:** One of the main classes of flavonoids, anthocyanin, functions as an antioxidant in a variety of stressful situations. Genes like OsDFR (dihydroflavonol 4-reductase) and OsC1 (MYB transcription factor) are involved in the manufacture of anthocyanins in rice. Anthocyanin biosynthesis genes are activated in response to phosphate shortage under P stress conditions.

b) **Acid Phosphatase release under nutrient stress:** One of the main adaptive reactions to the rhizosphere's lack of inorganic phosphate is the release of acid phosphatase (ACPs). Intracellular acid phosphatases recycle phosphorus within the plant by breaking down internal P-containing compounds, especially under severe deprivation. Genes that produce acid phosphatase in rice under P stress, such as OsPAP10a and OsPAP26.

Nutrient Uptake and management Strategies in Hydroponic

One of the main achievements of hydroponic systems is precise nutrient control, which allows plants to flourish in a soil-free environment. Hydroponics relies on nutrient solutions loaded with macro and micronutrients, in contrast to conventional agriculture where plants collect nutrients from the earth.

1. Sustaining the Concentration of Nutrients: One of the core ideas of hydroponics nutrient management. Maintaining the right nutrient content and ratio to satisfy the unique requirements of various growth stages requires meticulous solution formulation to guarantee that plants have access to all nutrients for growth and development.

2. PH adjustment: Moreover, it is directly effects nutrient availability and uptake by plants. For rice prefer PH range 5.5 to 6.5 which allow optimal absorption and healthy root. As a result, temperature, oxygenation, and water quality are all important aspects of nutrient management in hydroponics systems. To avoid nutritional imbalances and preserve plant health, high-quality water devoid of impurities like chlorine, chloramines, and heavy metals is crucial.

Limitations and Prospects for the Future

Soil-less farming has many benefits, but it also has certain drawbacks. The need for a large initial investment and technological know-how, particularly for commercial-scale operations in regulated surroundings, is one of the main obstacles. Maintaining optimal circumstances for plant growth demands competent administration and precise monitoring. Food demand is predicted to rise by up to 70% as the world's population is predicted to reach 9.6 billion by 2050. Conventional farming techniques might not be enough to meet this increasing need because over 80% of arable land is currently in use. In this regard, hydroponics allows for more crop yield with less resource input, opening up new avenues in agricultural science. This strategy not only minimises environmental impacts generally associated with greenhouses and nurseries but also boosts produce quality. As a result, hydroponics emerges as a feasible technique to contribute positively toward feeding the world's expanding population, while simultaneously addressing resource restrictions and environmental challenges.

Conclusion

To secure food security and sustain the livelihoods of the rapidly rising global population, enhancing rice production and producing nutrient-efficient, stress-resilient rice cultivars has become a critical goal. A multidisciplinary strategy is needed to address this issue, particularly since it is anticipated that nutritional resource constraints may worsen in the future. One significant technique involves improving varietal resistance to low-nutrient conditions by minimising environmental stressors through controlled settings, balanced nutrient solutions, and low-input growing systems. Additionally, there is a lot of promise for increasing the efficiency of nutrient uptake and utilisation through the use of contemporary molecular breeding techniques. These cutting-edge methods enable breeders to create rice varieties that are nutrient-efficient and climate-resilient, guaranteeing sustainable production and long-term food security.

References

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