Abstract

Groundnut (*Arachis hypogaea* L.) is an essential oilseed crop that plays a pivotal role in global agriculture and food security. However, its productivity is often restricted by minimal nutrient uptake, environmental stress, and dependency on chemical fertilizers. This study investigates an innovative, sustainable approach to enhance groundnut growth and productivity by integrating plant growth-promoting rhizobacteria (PGPR) and zinc oxide nanoparticles (ZnO NPs). The research aims to explain the synergistic effects of these biotic and abiotic agents on plant growth, and nutrient assimilation, laying a foundation for eco-friendly agricultural practices.

Rhizospheres soil samples from groundnut fields in Saurashtra, Gujarat, were collected and analyzed. A total of 84 rhizobacterial isolates were screened for their ability to synthesize plant growth-promoting (PGP) compounds, including indole-3-acetic acid (IAA), ammonia, hydrogen cyanide (HCN), gibberellins, and phosphate-solubilizing activity. The most promising isolates were identified as *Priestia megaterium* (RGKP3), *Bacillus haynesii* (RG12), and *Pseudomonas songnenensis* (RG8) based on 16S rRNA sequencing and Gram staining. These strains demonstrated robust plant growth promoting (PGP) traits, contributing to root growth, nutrient availability, and stress mitigation.

ZnO NPs were synthesized using the sol-gel method with zinc acetate as the precursor. Advanced analytical techniques, including UV-visible spectrophotometry, X-ray diffraction (XRD), scanning electron microscopy (SEM), and high-resolution transmission electron microscopy (HR-TEM), were employed to characterize the crystalline structure, morphology, and optical properties of the nanoparticles. A concentration of 400 ppm ZnO NPs was determined as optimal for biological applications, ensuring compatibility with PGPR strains without inhibiting bacterial growth.

The compatibility and synergistic effects of PGPR strains and ZnO NPs were assessed through growth curve analyses and seed priming experiments. Groundnut seeds treated with the combinations of PGPR and ZnO NPs were evaluated for germination rates, vigor index, and plant growth parameters under controlled conditions. Biochemical analyses were conducted to measure chlorophyll, carotenoid, flavonoids, sugars,

proteins, and proline content, providing insights into photosynthesis, metabolic activity, and stress resilience.

The combined application of PGPR and ZnO NPs significantly improved seed germination rates and vigor index, with *Priestia megaterium* (RGKP3) and ZnO NPs achieving the highest germination rate of 92%. Physical growth parameters, including root length, shoot length, number of leaves, and biomass, were noticeably enhanced by the combined treatments compared to individual applications. RGKP3+ZnO NPs resulted in the highest shoot and leaf development, while RG8+ZnO NPs were particularly effective in root proliferation.

Biochemical analysis revealed significant improvements in chlorophyll, carotenoid, and flavonoid levels, reflecting enhanced photosynthetic efficiency and antioxidant activity. The combination of RGKP3 and ZnO NPs produced the highest chlorophyll and carotenoid concentrations, contributing to increased photosynthetic rates. RG8+ZnO NPs demonstrated remarkable increases in sugar and protein contents, indicating enhanced metabolic activity and stress mitigation. Reduced proline levels in treated plants underscored the role of these treatments in reducing stress.

Among the three strains, *Priestia megaterium* (RGKP3) excelled in promoting photosynthetic efficiency and overall plant vigor. *Pseudomonas songnenensis* (RG8) exhibited a pronounced impact on biochemical traits, particularly in sugar and protein accumulation. *Bacillus haynesii* (RG12) contributed to plant growth and development but showed relatively moderate biochemical effects compared to RGKP3 and RG8.

The integration of PGPR and ZnO NPs offers a sustainable approach to enhancing crop productivity while minimizing environmental impacts. By improving nutrient uptake, promoting growth, and mitigating stress, this strategy reduces the reliance on chemical fertilizers, aligning with the goals of sustainable agriculture. *Priestia megaterium* in combination with ZnO NPs demonstrated the highest potential for improving photosynthetic efficiency and plant vigor, whereas *Pseudomonas songnenensis* showed exceptional biochemical enhancements. These findings pave the way for broader agricultural applications, including field trials under diverse environmental conditions.

Further research is recommended to optimize the formulations and explore the long-term effects of these treatments on soil health and crop yields. The study highlights the potential of integrating microbial inoculants with nanotechnology to revolutionize farming practices, ddressing global challenges in food security and environmental sustainability.