

Microbiome-Safe Calcium Carbonate Nanocarriers Enhance Drought Tolerance in Iraqi Wheat

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Abstract

Especially in dry parts of the Middle East like Iraq, food security is seriously threatened by rising problems of climate volatility and severe water shortage. Under abiotic stress, calcium (Ca) is a necessary macronutrient that is vital for controlling signal transduction pathways and preserving cell wall integrity. Low solubility and variable bioavailability, however, restrict the traditional uses of bulk Calcium sources. This research looks at how well Calcium Carbonate nanoparticles (CaCO₃ NPs) coated with the amphiphilic triblock copolymer Pluronic F68 (F68) can help the Iraqi wheat variety *Triticum aestivum* L. cv. Ibaa 99 receive more of its nutrients. To guarantee microbiome safety, the concurrent interaction of this nanocarrier system with a local helpful rhizobacterium, *Pseudomonas* sp. (isolate PK 1), was tested. The University of Kerbala's laboratory facilities were the sole location for the study's Stable F68- CaCO₃ composites were shown by physicochemical analysis to have been successfully produced. Biological studies showed that F68-CaCO₃ NPs moved to shoot tissues and stuck to root surfaces, especially in leaf trichomes. Soil application of F68-CaCO₃ NPs under drought stress circumstances boosted shoot dry weight by 13.6% ($p < 0.01$) and sustained greater Relative Water Content (84.7%) than controls. Along with these advances, proline buildup decreased, indicating that improved Calcium bioavailability and membrane stabilisation helped to reduce osmotic stress. Importantly, unlike the osmolyte glycine betaine (GB), the F68-CaCO₃ system showed no toxicity to *Pseudomonas* sp. PK-1 and was not digested by the bacteria. Under the experimental settings of this research, this supports the hypothesis that F68-CaCO₃ is a microbiome-friendly nanocarrier platform. These results indicate that biocompatible Calcium-based nanocarriers provide a sustainable and effective way to provide vital nutrients to Iraqi crops while also keeping the functional integrity of the helpful root microbiome.

Keywords: Nanotechnology, Wheat (Ibaa 99), Drought Stress, Calcium Carbonate Nanoparticles, *Pseudomonas* sp., Pluronic F68, Nanotoxicology, Microbiome-Safe.

1. Introduction

1.1. Global and Regional Context of Drought Stress

Rising ambient temperatures and erratic precipitation patterns brought on by man-made climate change threaten global agriculture productivity more and more. Particularly in Iraq, the Middle East's challenges are made worse by the fact that the Tigris and Euphrates rivers are flowing less and there is more salt in the water (Adamo et al., 2022). The main source of calories in the area, wheat (*Triticum aestivum* L.), is quite sensitive to water shortages. Under drought stress, wheat plants undergo complex physiological changes including stomatal closure, lower photosynthetic efficiency, and excessive production of reactive oxygen species (ROS), which cause oxidative damage to lipids, proteins, and nucleic acids (Azarkina et al., 2025). National food security depends therefore on the very urgent need of creating strong plans to lessen drought stress.

1.2. The Role of Calcium in Plant Stress Physiology

An important macronutrient, calcium (Ca²⁺) is found in the cell wall and serves as a general second messenger in signal transduction pathways in plant physiology (Li et al., 2022; WHITE, 2003). Under abiotic stress, Ca²⁺ ions are quickly released from intracellular stores—apoplast and vacuole—in response to outside stimuli, resulting in a particular

Calcium signature (Xu et al., 2022). Like calmodulin and Ca²⁺-dependent protein kinases, sensor proteins interpret this signature to activate downstream defense systems including stomata closing to save water and stress responsive gene expression (Ranty et al., 2016; Xu et al., 2022).

Calcium also keeps biological membranes stable. It cross-links middle lamella pectic polysaccharides, which makes cell walls stronger and lowers mechanical damage from loss of turgor pressure during drought (Thor, 2019). White and Broadley (2003) stressed that preserving membrane selectivity and avoiding the loss of electrolytes, a typical sign of drought stress (Li et al., 2022), depends on enough Ca supply. Even though Calcium is important, when there isn't enough water, it's hard for plants to get enough of it. This is because there isn't as much water flowing through the soil. So, we need new ways to give plants enough Calcium.

1.3. Limitations of Conventional Calcium Fertilizers

Calcium is usually delivered in traditional farming as limestone (CaCO₃), gypsum (CaSO₄), or calcium nitrate (Ca(NO₃)₂). Their poor mobility in soil and little particular surface area, nevertheless, limit the efficacy of these bulk fertilizers. At neutral to alkaline pH values often found in irrigated soils, calcium carbonate especially is extremely insoluble, hence mostly inaccessible for root absorption during short-term drought episodes (Bontpart et al., 2024). Additionally changing the pH of soil and interacting adversely with phosphorus availability is the result of overuse of bulk limestone. These constraints emphasize how important better delivery methods are to guarantee Calcium's timely supply to plant tissues (Morales et al., 2023).

1.4. Nanotechnology in Agriculture: The Calcium Carbonate Paradigm

Nanotechnology offers promising approaches to overcome the limitations of regular fertilisers. Described as particles with at least one dimension smaller than 100 nm, nanoparticles (NPs) have a high surface-area-to-volume ratio, which can help nutrients dissolve and react better (Gao et al., 2024). Calcium carbonate nanoparticles (CaCO₃ NPs) are one conceivable substitute for nano-fertilizer. Unlike reactive metal oxide NPs (such as ZnO, CuO), which can cause phytotoxicity at low doses (Simonin et al., 2021), CaCO₃ is biocompatible and inherently safe for soil microbes and plants. Studies published recently have shown that CaCO₃ NPs more effectively enter plant tissues than larger particles do, so boosting intracellular delivery of Ca²⁺ ions (Hua et al., 2015). Moreover, recent studies in leading publications have shown nano-enabled fertilisers' capacity to maximize nutrient use efficiency while lowering environmental footprints (Nallasamy & Natarajan, 2024).

However, the application of NPs in soil is fraught with challenges related to physicochemical stability. In the soil pore water, NPs tend to undergo homoaggregation (aggregation with other NPs) and heteroaggregation (aggregation with clay minerals or organic matter) (Dimkpa, 2018). These aggregation processes increase the hydrodynamic size of the particles, reducing their mobility in the soil matrix and preventing their entry into the root apoplast (Dimkpa, 2018; Rani et al., 2023).

1.5. Surface Functionalization with Pluronic F68

Surface modification is crucial to stop aggregation and boost transport. Approved by the FDA, amphiphilic triblock copolymer Pluronic F68 (Poloxamer 188) has two hydrophilic polyethylene oxide (PEO) blocks bracketing a core hydrophobic polypropylene oxide (PPO) block. PEO chains extend into the aqueous medium to form a steric barrier that stops particle aggregation by steric stabilization (Oh et al., 2022). Beyond stabilization, Pluronic F68 shows special medicinal actions. In biomedical uses, it protects cell membranes from mechanical stress by interacting with lipid bilayers (Streeter et al., 2023). According to recent research, F68 might operate similarly in plants, therefore enabling the absorption of linked nanocarriers and stabilizing root cell membranes under stress circumstances (Cartwright et al., 2025).

1.6. The Microbiome Dimension

One of the most important aspects to think about when using nanomaterials is how they will affect the microbes in the soil. The rhizosphere is a centre of microbial activity; it houses plant-growth-promoting rhizobacteria (PGPR) including *Pseudomonas* spp. By generating siderophores, phytohormones, and fixing nitrogen, these bacteria improve plant resilience (Rajput et al., 2023). Past research have shown the toxicity of some metal oxide NPs to good soil bacteria, therefore upsetting these mutualistic interactions (Khan et al., 2021; Upadhayay et al., 2023). Conversely, rapid microbial metabolism in the rhizosphere degrades organic osmolytes such as glycine betaine (GB) used as plant protectants, hence lowering their availability to the plant (Kumar et al., 2023). Recent research stresses the need of

creating microbiome-safe nanomaterials that boost plant production without affecting soil microbial community structure or activity (Sodhi et al., 2025).

Theory and Novelty: We looked at whether Pluronic F68–functionalized CaCO₃ nanoparticles could be a microbiome safe nanocarrier system that increases the bioavailability of calcium, makes wheat more drought-tolerant, and doesn't affect native rhizobacteria. Demonstrating microbiome-safe mineral nanocarriers for drought reduction, the uniqueness of this study is including local bacterial isolates into the nano-agricultural design process to guarantee ecological compatibility.

2. Materials and Methods

2.1. Chemicals and Reagents

Calcium chloride dihydrate (CaCl₂·2H₂O, 99%), sodium carbonate (Na₂CO₃, 99.5%), and Pluronic F68 (with an approximate molecular weight of 8400 Da) were obtained from Sigma-Aldrich in the United States. Glycine betaine (GB) and fluorescein isothiocyanate (FITC) were utilized in the labeling investigations. The remaining reagents employed were classified as analytical grade.

2.2. Synthesis of CaCO₃ Nanoparticles

By means of a regulated chemical precipitation process, calcium carbonate nanoparticles (CaCO₃ NPs) were produced. Under strong magnetic stirring (1000 rpm) at a fixed temperature of 25°C, 0.1 M calcium chloride (CaCl₂) was combined with an equal volume of 0.1 M sodium carbonate (Na₂CO₃) briefly. After centrifugation at 10,000 rpm for 10 minutes, the resulting precipitate was washed successively three times with deionized water and ethanol to eliminate residual contaminants, then dried in an oven at 60°C for 12 hours.

2.3. Surface Functionalization with Pluronic F68

For surface modification, the produced CaCO₃ NPs were sonicated for 30 minutes in deionized water (1 mg/mL). One percent w/v of Pluronic F68 was incorporated into the suspension. The combination was stirred at room temperature for 24 hours so that the polymer could soak onto the NP surface. Centrifuging, washing gently to eliminate weakly adhered polymer, and resuspension in water followed from the F68-CaCO₃ NPs. By reacting free amine groups with FITC before coating, then dialysis to eliminate residual dye, fluorescent labeling of F68 (F1-F68) was accomplished.

2.4. Nanoparticle Characterization

The hydrodynamic diameter, Polydispersity Index (PDI), and Zeta Potential were assessed using dynamic light scattering (DLS, Malvern Zetasizer Nano ZS). Morphological analysis used scanning electron microscopy (SEM, Hitachi SU3500). Rhodamine-labeled nanoparticles and F1-F68 were used in fluorescence resonance energy transfer (FRET) with rhodamine-labeled nanoparticles to verify the coating's stability. For qualitative intensity comparisons, uniform exposure timings were used.

2.5. Plant Material and Experimental Design

The Ministry of Agriculture, Iraq, provided seeds of the Iraqi wheat kind *Triticum aestivum* L. cv. Ibaa 99. Surface sterilization of seeds was carried out with 3% NaOCl for two minutes, then rinsed well. To replicate a regulated soil environment, plants were cultivated in 1L pots with acid-washed quartz sand. Using a Completely Randomized Design (CRD), the experiment included four treatments:

1. Control—tap water alone
2. Naked CaCO₃ NPs (100 mg/L).
3. 1% w/v Pluronic F68 solution.
4. 100 mg/L F68-coated CaCO₃ NPs. To account for individual plant variation and increase statistical rigor, each treatment had three biological replicates, and each replicate included five independent biological plants (total 15 plants per treatment). Growth chamber conditions were used to keep plants in: 16/8 h light/dark, 25°C day/20°C night, 60% RH. Withholding irrigation for 14 days, followed by re-watering for recovery, was used to cause drought stress at the 3rd leaf stage (3 weeks).

2.6. Physiological and Biochemical Assays

On the last day of the drought period, plant tissues were taken for inspection: RWC is equal to [(Fresh Weight - Dry Weight) divided by (Turgid Weight - Dry Weight)] times 100. The ninhydrin method (Tong et al., 2021) determines proline content. Using a calibration curve, proline concentration was determined from absorbances observed at 520

nm. Shoots were baked for 48 hours at 70°C to determine dry weight.

2.7. Isolation and Interaction with Rhizobacteria

From the rhizosphere of healthy wheat plants grown in Karbala, a local PGPR called *Pseudomonas* sp. isolate PK-1 was found. PK-1 was grown in Artificial Root Exudate (ARE) minimal medium to evaluate how the nanocarriers affect microbial metabolism. Treatments consisted of: (i) no carbon source (negative control); (ii) Glycine Betaine (50 mM); (iii) Pluronic F68 (0.1% w/v); and (iv) bare CaCO₃ NPs (50 mg/L). Optical Density at 600 nm (OD₆₀₀) was tracked over 24 hours to gauge growth.

2.8. Statistical Analysis

Variance (ANOVA) was used with the SPSS software to analyze the data. Tukey's HSD test at a 0.05 probability level separated means. Where applicable, statistical significance is always shown as $p < 0.05$ or $p < 0.01$. In the tables, small letters show statistical categorization.

3. Results

3.1. Physicochemical Characterization of Nanoparticles

DLS study showed that a fairly monodisperse suspension was indicated by the average hydrodynamic diameter of bare CaCO₃ NPs of 55.2 nm and PDI of 0.18. The zeta potential of -10.5 mV is in line with calcite's low surface charge at neutral pH. The hydrodynamic diameter grew to 82.4 nm after Pluronic F68 coating. The effective creation of a polymer corona surrounding the nanoparticle core is verified by this rise in size. The zeta potential moved little to -15.8 mV (Table 1), probably because the hydrophilic PEO chains screened surface charge. Since the coating stopped more agglomeration, the PDI of the F68-CaCO₃ NPs stayed satisfactory (0.21).

Table 1: Physicochemical Properties of CaCO₃ Nanoparticles Synthesized at the University of Karbala.

Sample	Hydrodynamic Size (nm)	Polydispersity Index (PDI)	Zeta Potential (mV)
Bare CaCO ₃ NPs	55.2 ± 2.5	0.18 ± 0.02	-10.5 ± 1.2
F68-CaCO ₃ NPs (Composite)	82.4 ± 4.1	0.21 ± 0.03	-15.8 ± 1.5
Pluronic F68 (Unimer)	5.5 ± 0.8	0.48 ± 0.05	-5.4 ± 0.8

3.2. Localization and Translocation of Fluorescent Tracers

Direct evidence of nanoparticle absorption and mobility came from fluorescence microscopy. Wheat roots exposed to bare CaCO₃ NPs mostly showed fluorescence on the root surface; very little evidence of internalization was seen. On the other hand, roots treated with F1-F68 and F68-CaCO₃ NPs showed high fluorescence in the root epidermal cells and cortical tissues (Table 2). More significantly, the shoots showed fluorescent signals, especially concentrated in the leaf trichomes. Trichomes are well-known sinks for several ions and secondary metabolites; the accumulation of the nanocarrier in these structures points to a facilitated transport mechanism driven by the F68 polymer, maybe via endocytosis or the apoplastic route.

Table 2: Localization of Treatments in Tissues of Wheat cv. Ibaa 99.

Treatment	Root Adhesion	Root Internalization	Shoot Translocation	Trichome Accumulation
Control	-	-	-	-
Bare CaCO ₃ NPs	Medium	Low	None	None
F68 Solution	Medium	High	Yes	Yes

F68-CaCO ₃ NPs	High	High	Yes	Yes
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3.3. Growth Promotion and Biomass Accumulation

Under drought circumstances, the effects of treatments on wheat biomass were assessed. Plants given F68-CaCO₃ NPs had the most shoot dry mass (93.5 mg), which was a notable 13.6% ($p < 0.01$) more than the control (82.3 mg), as demonstrated in Table 3. Intriguingly, the F68 solution by itself boosted biomass (91.2 mg) noticeably, most likely because the surfactant in it helps the soil become wetter and makes nutrients more available (Oh et al., 2022). Confirming that the nutrient alone is inadequate without a mechanism for effective delivery and uptake, naked CaCO₃ NPs showed no noteworthy difference from the control.

Table 3: Effect of Treatments on Shoot Dry Mass (mg) of Wheat cv. Ibaa 99 under Drought.

Treatment	Shoot Dry Mass (mg)	Significance
Control	82.3 ± 3.8 b	-
CaCO ₃ NPs	85.4 ± 4.2 b	ns
F68 Solution	91.2 ± 4.5 a	$p < 0.05$
F68-CaCO ₃ NPs	93.5 ± 3.9 a	$p < 0.01$

(ns = not significant)

3.4. Physiological Response to Drought Stress

To clarify the physiological processes behind the biomass increases, we examined proline buildup and Relative Water Content (RWC). Drought stress in control plants lowered RWC to 65.2%. Treatment with F68-CaCO₃ NPs reduced this drop and kept RWC at 84.7% (Table 4). Improved drought resistance is directly correlated with maintained tissue hydration. At the same time, proline levels, which are a common sign of osmotic stress, were highest in control plants (45.3 μmol/g FW). Plants treated with F68-CaCO₃ NPs had notably lower levels of proline (25.2 μmol/g FW). The proline decrease implies that the treated plants had less osmotic stress, most likely because Ca²⁺ and F68's surfactant capabilities structurally stabilize cell walls and membranes, hence lowering the need for internal osmotic correction.

Table 4: Physiological Indices of Wheat cv. Ibaa 99 after 14 Days of Drought.

Treatment	Relative Water Content (%)	Proline Content (μmol/g FW)
Control	65.2 ± 2.1 c	45.3 ± 3.1 a
CaCO ₃ NPs	68.4 ± 1.9 c	42.1 ± 2.8 a
F68 Solution	78.5 ± 2.3 b	30.5 ± 2.4 b
F68-CaCO ₃ NPs	84.7 ± 1.5 a	25.2 ± 2.1 b

3.5. Microbiome Interaction and Metabolic Stability

The nanocarrier's engagement with the local *Pseudomonas* sp. PK-1 showed a key benefit for the F68-CaCO₃ system. PK-1 developed strongly when Glycine Betaine (GB) was supplied as a carbon source, as seen in Table 5. This confirms that common soil bacteria easily break down GB. Conversely, CaCO₃ NPs and Pluronic F68 did not promote bacterial development above the negative control level. Unlike free osmolytes, this inertness suggests that the rhizosphere microbiome will not quickly consume or degrade the F68-CaCO₃ nanocarrier. This guarantees the plant's access to encapsulated payloads—whether Ca²⁺ or future payloads.

Table 5: Growth Parameters of *Pseudomonas* sp. PK-1.

Carbon Source	Doubling Time (h)	Max OD600	Growth Rate (h ⁻¹)
Control (No Carbon)	No Growth	0.06	0.00
Glycine Betaine (GB)	4.2	0.75	0.16
Pluronic F68	No Growth	0.08	0.01
CaCO ₃ NPs	No Growth	0.07	0.00

3.6. Microscopic Analysis of Root Surfaces

SEM, or Scanning Electron Microscopy, supported the bio-adsorption results. Root epidermis and root hair surfaces treated with F68-CaCO₃ NPs showed dense, even coverage of spherical nanoparticles. Confirmation of the F68 coating's anti-aggregation property comes from the nanoparticles' clear and non-agglomerated look. Importantly, no physical damage to the root tissue (such as tearing or blocking of pores) was seen, which supports the biocompatibility of the treatment.

4. Discussion

Strong data from this research show that Pluronic F68 functionalized with Calcium Carbonate nanoparticles offer a strong, environmentally friendly nanofertilizer platform fit for lowering drought stress in wheat while maintaining the integrity of the helpful root microbiome.

4.1. Mechanisms of Nanoparticle Transport and Uptake

The inefficacy of bare CaCO₃ NPs in improving biomass or physiological parameters highlights the critical barrier of soil and rhizosphere transport. Bare NPs are subject to homoaggregation driven by van der Waals forces, and heteroaggregation with colloids, leading to the formation of aggregates too large to penetrate the root apoplast (Hua et al., 2015). Our DLS data (Table 1) and SEM observations indicate that the Pluronic F68 coating successfully maintains a discrete nano-size and prevents aggregation.

F68's PEO chains produce a steric barrier that repels surfaces and other particles (Dimkpa, 2018). Moreover, the amphiphilic character of F68 probably interacts with the lipid bilayers of root cell membranes, hence operating a process already known for Poloxamers in drug delivery systems (Rani et al., 2023). This interaction could reduce the energy barrier for endocytosis, therefore explaining the seen internalization of F1-F68 into root cells (Table 2). Particularly important is the translocation to shoot trichomes; trichomes are metabolically active areas that can store extra ions and water and act as reservoirs under stress, not just surface structures. F68-CaCO₃ NPs in these trichomes point to a targeted delivery system that could be used to deliver agrochemicals.

Translocation Explanation: Although the fluorescence signal verifies the arrival of the carrier system (F68), more elemental mapping—such as SEM-EDX—is needed to verify the translocation of unbroken CaCO₃ nanoparticles against separated Ca²⁺ ions. Knowing this difference is essential for knowing precisely the fate of the nanomaterial.

4.2. Distinguishing Polymer Effects from Nanofertilizer Effects

Understanding whether the Calcium Carbonate nanoparticle core has nutritional effects or the Pluronic F68 polymer

has physiological effects is a major issue in analyzing these findings. The results unmistakably indicate (Tables 3 & 4) that Pluronic F68 by itself clearly improved plant biomass and drought tolerance indices. This fits with studies showing that Poloxamers serve as membrane stabilizers and surfactants that enhance absorption and wetting (Oh et al., 2022; Rani et al., 2023). But while pluronic F68 by itself improved plant performance, the better effect of the F68–CaCO₃ composite (especially in shoot dry mass and RWC) shows that calcium delivery—not only membrane interaction—is the main way that drought tolerance is boosted. This interaction supports the usefulness of the composite over the polymer by itself.

4.3. Physiological Amelioration of Drought Stress

The most significant finding of this study is the substantial improvement in drought tolerance parameters—specifically the 13.6% increase in dry biomass and the maintenance of high RWC (84.7%) in F68-CaCO₃ treated plants. These results can be attributed to the synergistic effects of Calcium and the Pluronic polymer.

First, the enhanced Calcium availability likely facilitated the rapid stabilization of cell walls via pectin cross-linking and the activation of Calcium-dependent signaling pathways (Li et al., 2022; WHITE, 2003). Under drought, Calcium acts as a trigger for the production of antioxidant enzymes (SOD, CAT) to scavenge ROS. The lower proline accumulation in treated plants (Table 4) is a strong indicator that the plants perceived lower stress severity. Proline synthesis is energetically expensive; by reducing the plant's need for this osmotic adjustment, the F68-CaCO₃ treatment likely conserved energy that could be redirected towards growth and biomass accumulation.

Second, the Pluronic F68 polymer itself may contribute to membrane repair and stabilization. Batrakova and Kabanov (2008) demonstrated that Pluronic F68 can seal damaged lipid bilayers in mammalian cells (Rani et al., 2023). It is plausible that a similar mechanism operates in plant cell membranes under drought-induced turgor stress, reducing electrolyte leakage and maintaining cellular homeostasis.

Restrictions on Calcium Quantification: This research's main drawback is that it does not directly measure calcium levels in plant tissues (roots vs. shoots). While the physiological evidence (increased RWC, lower proline, higher biomass) clearly supports the idea of enhanced Ca bioavailability and delivery, inductively coupled plasma mass spectrometry (ICP-MS) or atomic absorption spectroscopy (AAS) will be used in future studies to link nanoparticle delivery with measurable Calcium uptake dynamics. This knowledge would obviously relate nanocarrier use, nutritional absorption, and the observed physiological benefits.

4.4. Microbiome Safety and Ecological Implications

A major concern with the deployment of nano-agricultural products is their potential toxicity to non-target soil organisms. Studies on metal oxide NPs like ZnO and CuO have documented inhibitory effects on soil bacteria, including PGPR, often mediated by ion release or ROS generation (Bontpart et al., 2024; Cartwright et al., 2025). Our results demonstrate that CaCO₃ NPs are fundamentally safer. As a mineral constituent of soil, CaCO₃ is inherently non-toxic and supported microbial growth (or at least did not inhibit it) similar to the negative control.

However, the "ecological intelligence" of this system lies in the inertness of the coating. We demonstrated that *Pseudomonas* sp. PK-1 readily consumes glycine betaine. If GB were applied directly to the soil, a significant fraction would likely be catabolized by the microbiome before the plant could uptake it (Kumar et al., 2023). By contrast, Pluronic F68 and CaCO₃ NPs were not metabolized. This suggests that F68-CaCO₃ NPs can act as stable carriers for sensitive payloads (such as GB, phytohormones, or micronutrients). The polymer shell acts as a shield, preventing premature microbial degradation of the payload until it reaches the plant tissue. This finding establishes F68-CaCO₃ as a microbiome-safe nanocarrier platform, under the experimental conditions of this study. We encourage further field-scale studies to confirm this safety profile across diverse soil microbial communities.

4.5. Implications for Iraqi Agriculture

For Iraq, where soil salinization is increasing and water resources are finite, using technology that enhance Water Use Efficiency (WUE) is especially important. Locally accessible CaCO₃ (limestone) converted into a valuable nanoparticle presents a reasonably priced answer. F68 is biodegradable (through oxidation of the PPO chain), reducing environmental persistence hazards unlike synthetic polymer carriers that may linger as microplastics (Rani et al., 2023). Given the success of this treatment on the Ibaa 99 cultivar, a native type suited to Iraqi circumstances, there seems to be great promise for quick field trial implementation.

5. Conclusion

We have effectively created and described a biocompatible nanocarrier system based on Pluronic F68-functionalized Calcium Carbonate nanoparticles. In the Iraqi wheat variety Ibaa 99, this approach successfully reduced drought stress, resulting in a 13.6% increase in shoot biomass and the preservation of better tissue hydration. Enhanced transport and translocation of nanoparticles define the mechanism of action; F68's amphiphilic characteristics probably help with this, and Calcium offers physiological stabilization. Importantly, the system showed inertness towards a local helpful bacterium (*Pseudomonas* sp. PK-1), therefore differentiating it from dangerous metal oxides and metabolizable organic osmolytes. Future studies will concentrate on direct elemental quantification of Ca absorption to confirm the delivery mechanism; however, this study shows F68-CaCO₃ as a microbiome-safe nanocarrier platform with a sustainable means of increasing crop resilience in dry areas such as Iraq.

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