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Nigeria, Improving Plant Nutritional Content in Drought Conditions

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Timing Rhizosphere Bacteria to Combat Drought-Induced Micronutrient Deficiencies in Nigeria

In Nigeria, prolonged droughts are no longer rare events as they are becoming increasingly frequent (Naumann et al., 2018). For many farming families, this means more than just declining harvests. It results in children growing up without sufficient iron, vitamin A, or other essential nutrients required for healthy development (Adebayo, 2024). As climate change intensifies drought conditions, it is not only the quantity of food that is threatened, but also its nutritional quality (Maseko et al., 2019). Micronutrient malnutrition (often called hidden hunger) affects millions across Nigeria and the broader Sub-Saharan region (Adebayo, 2024). Micronutrient malnutrition has severe health implications, leading to stunted growth and development, blood conditions such as anemia, pregnancy complications such as stillbirth, increased risk of disease and infection, blindness, and many other life-threatening conditions (World Health Organization, n.d.). These challenges are made worse by declining agricultural productivity and limited access to diverse, nutrient-rich foods. One promising approach lies in the use of plant-growth promoting rhizobacteria (PGPR). However, rather than relying on traditional methods of early or continuous application, this research proposes a strategic shift of applying the bacteria during critical stages of drought stress to maximize effectiveness while minimizing cost.

Background Review

Family and General Population

The prevalence of poverty in Nigeria adds additional barriers to food security for the nation's citizens. With around 70% of the population surviving on "under one dollar per day" (Matemilola & Elegbede, 2017), access to quality crops becomes increasingly difficult. This ties into the concerning rates of food insecurity, equating to 79% in low-income families and 71% for rural families (Matemilola & Elegbede, 2017). Thus, it is essential that these food insecurity rates be addressed to increase the quality of life for those living in Nigeria. The struggle for families to obtain food lies in Nigeria's current struggle to produce enough crops to sustain demand. Nigeria's declining agricultural productivity has prompted dependency on food importation (Matemilola & Elegbede, 2017), driving forth difficulties for families. These issues in production only continue to be worsened by global climate change. Additionally, the poverty present in Nigeria adds an additional hurdle to creating a solution to food insecurity, the need for the solution to be easily financially accessible. Implementation by farmers is essential to any agricultural solution and thus farmers already struggling to meet financial needs require a solution that is affordable given their circumstances.

Potential Solutions

Dietary supplementation of micronutrients has shown effective results in curbing the effects of malnutrition in Africa; However, the results are not widespread nor uniform (Scott et al., 2020). The discussion of supplements' ability to reduce malnutrition is mixed in conclusions, likely due to supplements only offering mitigation of effects and not addressing root causes. Therefore, improving the consumption of whole foods in diets is a more effective approach to countering malnutrition. The body is better able to absorb micronutrients from whole foods, due to intake at proper concentrations which increases bioavailability, and whole foods contain a diversity of micronutrients which promotes nutrient

interactions (Incze, 2019). Therefore, targeting crop cultivation provides the greatest potential to combat malnutritional issues.

Current initiatives to reduce micronutrient malnutrition using whole foods include the use of genetically modified biofortification. However, biofortification has not seen widespread effectiveness due to cost prohibitions, outright rejection of synthetic solutions due to environmental harm, and banning of genetically modified crops for cultural beliefs (Mmbando et al., 2024). Despite the diversity of cultures present in Nigeria, resistance against genetic modification is widespread and therefore, a developed solution needs to be a natural enhancement to the current agricultural system.

A promising alternative direction targets naturally occurring systems in the plant roots' rhizosphere, offering a biological approach that is compatible with agricultural practices already being explored in Nigeria. For background: the expansion of plant roots in soil creates an area around the root structure called the rhizosphere, which is characterized by root secretions (exudates) of beneficial carbon compounds, sugars, and amino acids (Bittencourt et al., 2023). The root exudates recruit beneficial bacteria to colonize the rhizosphere and create symbiotic relationships with the plant host in order to facilitate nutrient uptake, suppress pathogens, and modulate abiotic stressors (Chepsergon & Moleleki, 2023). These processes improve the assimilation of nutrients by converting nutrients and minerals into compounds with greater bioavailability. Their ability to stimulate growth via nutrient cycling creates potential to improve plant growth as a biological alternative to synthetic fertilizers. New findings reveal the use of those plant-growth promoting rhizobacteria (PGPR) in inoculations to improve crop yield and plant quality during drought and therefore increase micronutrients in diet to counter malnutrition. PGPR are able to increase plant growth and nutritional quality through both indirect and direct mechanisms including nutrient cycling and resistance to stressors (Vejan et al., 2016). Beyond nutrient enhancement, PGPR are a sustainable and organic solution, increasing potential acceptance and usability.

Problem

Despite effective results of PGPR treatments in Nigeria, current focus on early (at the beginning of each growing season) and sustained treatments results in large volumes of bacteria required for inoculation usability, and use of highly specific strains greatly reduces large scale feasibility in Nigeria (Adedeji, 2020). These current methods lead to PGPR being used during seasons that do not incur a drought, resulting in increased volumes and cost for bacteria that may not have been necessary. Therefore, currently, the commercial use of PGPR treatments is not economically viable for small-scale Nigerian farmers (Adedeji, 2020).

For a resource-constrained Nigerian farmer, the economic value of PGPR depends not simply on whether the treatment works, but on whether the inputs required to maintain that treatment are affordable. Applying an inoculant throughout an entire growing season creates costs even when drought conditions are absent. A strategy that instead allows farmers to respond to drought only when it occurs could reduce unnecessary applications while retaining the protective benefits of PGPR. Thus, the central question for Nigerian implementation is not whether PGPR can improve drought tolerance, but whether its application can be timed efficiently enough to make the technology accessible to farmers who cannot afford unnecessary agricultural inputs. The subsequent research found PGPR can potentially be shifted from a preventative, broad-season treatment to a targeted, drought-triggered treatment, making it substantially more practical for resource-constrained farmers while preserving or improving nutritional quality.

Methodology

Proposed Inoculant Solution

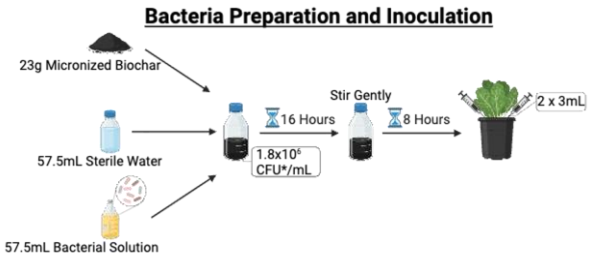
There are many different bacteria classified as PGPR. For the purposes of this research, the commercial product "Continuum" by Impello Biosciences was selected. By using a commercially available product, this research simulates the materials that would be readily and cost effectively available to Nigerian farms

that may be facing economic hardship as compared to a laboratory self-developed inoculant. This inoculant was specifically selected for its blend of diverse co-cultured PGPR which allows for wide-spread effective stress tolerance in host plants. The inoculation solution was amended with biochar, which is derived from the anaerobic thermal processing of organic matter to create a "carbon-rich" solid (Ye et al., 2016). The use of biochar with PGPR has been found to be influential on PGPR community size, formation, and diversity (Fan et al., 2023). Thus, its chemical properties suggest function as a habitat for PGPR and lead to hypothesizing of its ability to be a suitable carrier for PGPR to increase inoculation efficacy in difficult conditions such as nutrient poor and drought stressed Nigerian soil. Therefore, biochar was used as a base for the inoculation to provide a suitable habitat for the PGPR to improve establishing during drought stress.

The inoculation process follows as outlined in the figure below.

Figure 1

Bacterial Inoculation Process



Experimental Design

This study sought to examine how differing timings of inoculation affect nutritional preservation. This way, the bacterial solution can be used only when needed, not preventatively at the start of the growing season. To assess the effect of inoculation timing as well as drought intensity, the crops were split into 12 treatments. Three drought intensities (85%, 60%, and 35% field capacity) were used to determine whether the proposed treatment remained effective as drought severity increased, reflecting the need for an intervention capable of functioning under variable drought conditions. Four inoculation timings were compared because timing determines both treatment effectiveness and the quantity of inoculant required, directly affecting the economic feasibility of adoption by Nigerian farmers. These inoculation timings included no inoculation, early inoculation (current methodology), middle-stage inoculation, and late-stage inoculation (waiting until drought starts; most cost effective). Lagos spinach was selected to test because it represents a crop commonly used in Nigerian cuisine while also providing substantial nutritional value. Rather than testing PGPR on a crop chosen solely for laboratory convenience, this study used a locally relevant leafy vegetable to evaluate whether drought-resilience interventions could preserve the nutritional quality of food that Nigerian households could realistically consume.

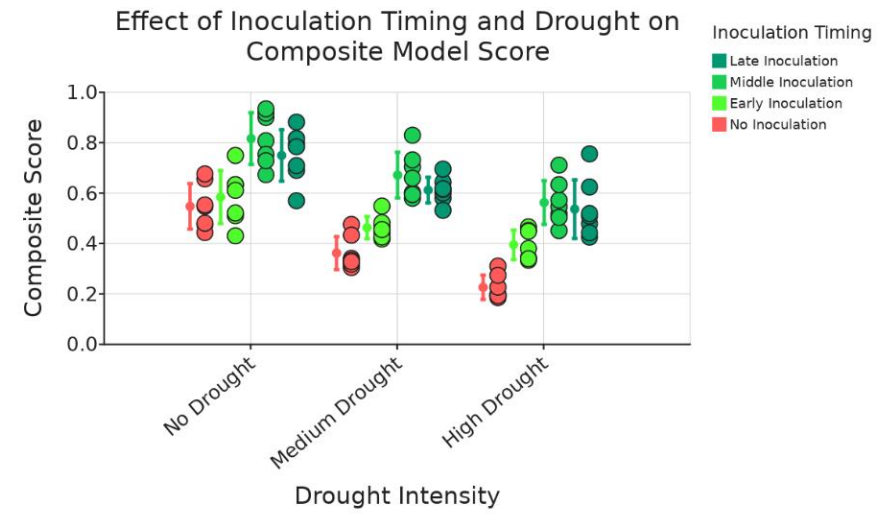
Results

To assess trends in nutritional content across inoculation timing, the collection of four dependent variables (all assessed for nutritional applicability in conclusion) was conducted: biomass (g), chlorophyll content (µg/g tissue), Brix (°Bx, total dissolved solids), and iron content (mg/100g dry matter). These variables were combined into a composite score representing overall plant performance and measured nutritional characteristics, with 1 representing the highest score and 0 representing the lowest.

Composite Nutritional Model Results

Graph 1

The Combined Effect of Inoculation Timing and Drought on Composite Score



Note: Dot indicates mean and bars represent ±1 standard deviation.

When comparing the mean composite nutritional score, inoculated Lagos spinach reported higher scores than non-inoculated Lagos spinach, indicating greater nutrition in inoculated plants (See Graph 1). This was the expected trend for proving inoculation successfully improved drought-stress tolerance. Upon mean comparison between only the inoculated Lagos spinach, middle-stage inoculation yielded the greatest score (nutrition), followed by late, and then early (See Graph 1). Thus, the results indicate improved Lagos spinach nutritional quality using the proposed inoculations that are more cost accessible for Nigerian farmers. These ideas will be elaborated on in the analysis and conclusion. Moreover, the mean composite scores for middle and late inoculation began to converge, with greater drought intensity, indicating greater effectiveness under worsening drought conditions (See Graph 1). Results were similar across the range of drought intensities and 2-way ANOVA statistical testing revealed p-values <0.01 for the impact of inoculation timing.

Analysis and Conclusion

Timing of inoculation was found to have a significant impact on crop nutritional quality, with middle-stage inoculation producing the greatest effectiveness across all drought conditions and measured variables. This was followed by late-stage inoculation, and then early-stage inoculation. These results challenge conventional agricultural practices, which emphasize early application. Instead, the findings indicate that inoculating closer to, or during, drought conditions is more effective for preserving nutritional quality in crops and makes the solutions more economically accessible to Nigerian farmers.

These results also help address key limitations associated with PGPR use. By demonstrating successful inoculation at lower concentrations (concentrations in experiment ranging from 100 to 10000 times lower than current practices), reduced total volumes (due to inoculation only in late season and only when necessary), and across varied growth stages (occurring during already stressed stages like drought), this study establishes not only practical methodology, but more effective results. In particular, the biochar-based inoculant showed clear success in maintaining nutritional quality when applied during late-stage growth under drought conditions. As a result, this approach offers a more feasible solution for farmers by reducing both input costs and labor demands while improving effectiveness at increasing crop nutrition.

However, this study operates under the assumption that increased accessibility to rhizosphere bacterial treatments will lead to greater usage. This relationship cannot be definitively established without further investigation into real-world implementation within West Africa. Despite this, while adoption rates remain uncertain, it can be concluded that PGPR treatments can be delivered in a more accessible and resource-efficient manner. Even with this limitation, such solutions hold strong potential to alleviate malnutrition in Nigeria by improving the nutritional quality of drought-stressed crops.

For implementation in Nigeria, the proposed treatment could be incorporated into existing agricultural extension systems rather than requiring farmers to adopt an entirely new production system. Farmers would apply the inoculant only when drought conditions reach a predetermined threshold, reducing the need for routine applications throughout the growing season. Agricultural extension workers could provide guidance on identifying drought onset and applying the appropriate inoculant concentration. Because the proposed methodology reduces the quantity of inoculant required, it could also lower the financial barrier associated with adoption. Further field research in Nigerian soils and farming systems would be necessary before large-scale deployment, but this approach provides a framework for adapting PGPR technology to the economic constraints of Nigerian agriculture.

The observed trends in plant physiological responses have direct implications for human nutrition. Increases in chlorophyll content and biomass production enhance the plant's capacity for nutrient synthesis. As a result, the inoculant's ability to elevate both factors suggests an increase in overall metabolic activity, which contributes to improved nutritional quality. These relationships are particularly important, as chlorophyll and biomass are closely linked to a plant's ability to produce and store essential nutrients. Brix and iron content provide more direct indicators of nutritional value. Brix serves as a measure of soluble solids, usually dominated by sugars. The observed increases in Brix across inoculated treatments indicate a higher concentration of these compounds, thereby improving nutrient availability within the crop. Similarly, iron is one of the most widespread and critical micronutrient deficiencies in Nigeria with serious health consequences including anemia and impaired development (Abbaspour et al., 2014). Limited dietary access remains the primary cause of iron deficiency (Kiani et al., 2022), making agricultural interventions particularly relevant. The demonstrated increase in iron content suggests that these inoculation strategies could play a critical role in improving dietary iron intake and reducing deficiency rates.

Previous research has identified current inoculation methods as prohibitive, largely due to the need for high volumes and early application. In contrast, this study demonstrates that effective results can be achieved with lower concentrations and targeted applications during critical growth stages. This allows inoculation to be performed immediately prior to or during drought conditions, while still maintaining stronger nutritional outcomes than if done at the beginning of each growing season. Additionally, the solution utilizing naturally occurring soil bacteria increases potential acceptance as compared to other attempted solutions.

In Nigeria, where drought, economic constraints, and micronutrient deficiencies intersect, agricultural solutions must be both biologically effective and economically practical. This research demonstrates that inoculation timing can influence the nutritional quality of drought-stressed crops and suggests that PGPR can be shifted from a preventative treatment toward a targeted response to drought. The next step is to determine how it can be adapted to Nigerian soils, crops, farmers, and agricultural systems. By reducing unnecessary inputs while preserving crop nutrition, targeted PGPR application could provide Nigerian farmers with a more accessible tool for maintaining the nutritional value of food under increasing drought pressure.

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