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Plant growth-promoting bacteria: Advancing sustainable agriculture in north Africa

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Abstract. The overreliance on chemical nitrogen (N) fertilizers has led to environmental degradation, soil health decline, and rising costs. This challenge is especially relevant in North Africa, where fertilizer use remains relatively low, yet the demand for higher agricultural productivity and food security continues to grow. Plant Growth-Promoting Bacteria (PGPB) have emerged as an eco-friendly alternative to synthetic fertilizers, supporting plant development through N fixation, phytohormone production, nutrient solubilization, and pathogen control. Genera such as Azospirillum and Rhizobium are among the most studied, showing the ability to enhance N availability, crop resilience to drought and salinity, and overall yields. This review synthesizes current knowledge on PGPB in North Africa, with emphasis on Algeria, Morocco, and Tunisia. Native strains adapted to arid and semi-arid conditions have shown promising results in improving soil fertility and crop performance. However, limited farmer awareness, resistance to change, environmental variability, and weak policy support hinder large-scale adoption. Advancing PGPB use requires research on native strains, farmer training, and enabling policies. Harnessing PGPB can reduce dependence on chemical inputs while promoting sustainable agriculture, environmental protection, and food security in the region.
Keywords: Azospirillum, Nitrogen fertilizer, Rhizobium, Semi-arid, Soil Health.

Introduction

In recent years, the use of chemical fertilizers in agriculture has increased substantially to improve productivity and meet the demands of a growing world population. Fertilization practices are not only costly but have also been identified as significant contributors to greenhouse gas (GHG) emissions (Zhiyong *et al*., 2024). Consequently, farmers are now faced with the dual challenge of enhancing production efficiency while simultaneously reducing environmental impact. In this context, plant growth-promoting bacteria (PGPB) have gained attention for their potential to support sustainable agriculture (Olanrewaju *et al*., 2017), as microbial inoculants (Arora *et al*., 2024). The use of PGPB is considered a sustainable and environmentally friendly strategy to enhance crop yields, address food security concerns, and reduce dependence on nitrogen(N)-based fertilizers (Gasparotto *et al*., 2022). Unlike synthetic fertilizers, PGPB are cost-effective, renewable, and contribute to long-term soil health while promoting plant growth.

In North African countries, the use of N fertilizers remains limited, constraining agricultural productivity and, consequently, the region's capacity to ensure food security for its growing population (Elrys *et al*., 2019). Estimating N flows is a critical tool for understanding and improving the sustainability and equity of global food systems (Lassaletta *et al*., 2016). In this context, enhancing crop N use efficiency while minimizing synthetic N inputs is essential within a sustainable agricultural framework (Dellero, 2020).

Among the promising strategies to reduce reliance on synthetic fertilizers is the use of PGPB, a diverse group of microorganisms known for their beneficial interactions with plants. The PGPB can enhance N availability through their remarkable capacity to synthesize phytohormones, which stimulate extensive root development (Hungria *et al*., 2021). Understanding the mechanisms by which PGPB facilitate plant growth is therefore crucial for advancing sustainable agriculture, particularly in regions such as North Africa, where optimizing agricultural inputs is critical for economic development and long-term food security. The most widely studied microorganisms for improving plant N content are symbiotic rhizobia. Additionally, other diazotrophic bacteria, such as Azospirillum spp., are used as inoculants (Bourscheidt *et al*., 2019). However, it is generally acknowledged that in free-living N-fixing bacteria, the contribution of fixed N to plant nutrition is relatively limited, with their benefits extending beyond N provision to include root stimulation and stress tolerance (James and Olivares, 1997).

Contextualization and analysis

This literature review aims to examine the current state of knowledge on PGPB and their role in plant growth promotion, with a focus on their potential applications and implications for agriculture in North Africa. By synthesizing existing research and highlighting key knowledge gaps, this review seeks to inform researchers, practitioners, and policymakers working to enhance agricultural productivity while minimizing environmental impacts in this critical region.

Agricultural Practices and N Use in North Africa

Agriculture plays a vital role in the economies and societies of North African countries (Jeblia and Ben Youssef, 2017). Despite ongoing efforts to enhance agricultural productivity, the region faces several persistent challenges. These include arid climatic conditions, limited rural transportation infrastructure, and unfavorable soil properties, all of which contribute to a negative agricultural trade balance (Alvarez-Coque, 2012). As a result, many countries in the region are highly dependent on imports of staple agricultural products such as cereals, meat, and dairy. With the population in Africa projected to grow significantly by 2050, accelerating agricultural production has become critical to ensuring food security (Elrys *et al*., 2020).

Nitrogen fertilizers are essential for improving crop yields, particularly in Africa, where average N input remains considerably below global standards. Although fertilizer use has increased since the 1960s and 1970s, many African countries still apply less than 7 kg of fertilizer per hectare annually (Elrys *et al*., 2020). In contrast, countries such as Brazil and the United States apply substantially higher rates, exceeding 100 kg N per hectare, highlighting the disparity in fertilizer use and its potential impact on productivity (Bourscheidt *et al*., 2019; Pedreira *et al*., 2024; Yasuoka *et al*., 2023).

According to FAO data from 2013 to 2022, N fertilizer use in North Africa reveals important trends in agricultural practices and highlights the region's struggle to optimize fertilizer use. Morocco emerges as the leading consumer of N fertilizers in the region, withan average annual consumption ofapproximately 216,000 tons (Figure 1). This equates to roughly 50–60 kg of N per hectare of arable land. The increasing demand for food has driven up fertilizer consumption in recent decades, though efforts are ongoing to enhance nutrient use efficiency and minimize environmental impact. Tunisia also demonstrates significant N fertilizer usage, particularly for crops such as wheat, olives, and various vegetables. The country consumes around 81,000 tons of N fertilizer annually(Figure 1). However, Tunisia's heavy reliance on imported fertilizers poses sustainability concerns, especially considering fluctuating global market prices that affect affordability and availability.

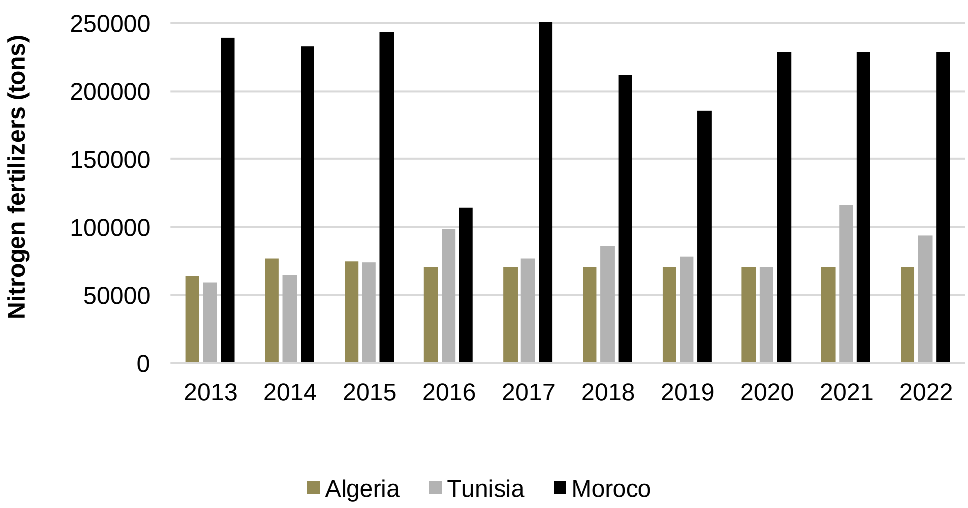

Figure 1. Nitrogen fertilizer consumption in North Africa from 2013-2022 (FAO STAT)

The In contrast, Algeria reports lower N fertilizer consumption, estimated at approximately 70,000 tons per year, among the lowest rates in North Africa (Figure 1). Although government initiatives have promoted fertilizer use to increase cereal production, challenges remain. Boulelouah *et al*. (2022) note that N fertilization practices in Algeria are often inconsistent and poorly managed, largely due to insufficient knowledge and training among farmers, resulting in inefficient and sometimes excessive application.

Limited financial resources, low economic returns, high input costs, insufficient extension services, and inadequate farmer knowledge are key factors that have significantly constrained the adoption of fertilizer use in North Africa (Ciceri and Allanore, 2019; Elrys *et al*., 2019). These limitations have contributed to soil nutrient depletion and pose a serious challenge to sustaining agricultural productivity in the region (Elrys *et al*., 2020). While there is a recognized need to increase N fertilizer application to enhance soil fertility and support food security across Africa (van Ittersum *et al*., 2016), this must be approached with caution. Excessive or poorly managed fertilizer use can result in N losses to the environment, exacerbating issues such as water pollution and greenhouse gas emissions. In this context, the use of plant growth-promoting bacteria (PGPB) presents a promising, cost-effective, and environmentally sustainable alternative to improve nutrient availability and crop performance under resource-limited conditions.

Plant Growth-Promoting Bacteria

Plant growth-promoting bacteria are a group of beneficial microorganisms that inhabit the plant rhizosphere and enhance plant development through a variety of mechanisms. These bacteria can directly supply essential nutrients that are often limited in the soil, serving as an environmentally friendly alternative to chemical fertilizers. Additionally, they may indirectly promote plant health by protecting against soil-borne pathogens (Glick, 2012).The PGPB encompasses adiverse range of genera,including Bacillus, Serratia, Azospirillum, Arthrobacter, Enterobacter, Burkholderia, Alcaligenes, Azotobacter, Pseudomonas,and Klebsiella (Guerrieri *et al*., 2020).

The plant growth-promotion mechanisms are typically categorized as either direct or indirect. Direct mechanisms involve specific bacterial functions such as the synthesis of phytohormones, including auxins (e.g.,indole-3-aceticacid [IAA]), cytokinins, gibberellic acid, and ethylene modulation, as well as biological N fixation, phosphorus solubilization, and iron chelation via siderophores. Indirect mechanisms refer to the inhibition of phytopathogens through traits such as the production of ACC deaminase, antibiotics, cell wall-degrading enzymes, hydrogen cyanide, and the induction of systemic resistance in host plants (Tabassum *et al*., 2017). Furthermore, PGPB contribute to plant resilience under abiotic stress conditions such as salinity, drought, and soil acidity. They also participate in the bioremediation of toxic heavy metals and the degradation of synthetic chemical compounds (Yousef, 2018; Warrad *et al*., 2020).

Although PGPB naturally occur in soils, their native populations are often insufficient to outcompete established microbial communities in the rhizosphere. To maximize their beneficial effects, it is typically necessary to inoculate soils with selected strains, thereby increasing their population density and efficacy in promoting plant growth (Shi *et al*., 2023).

Among PGPB, the genus *Azospirillum,* comprised of gram-negative, free-living diazotrophic bacteria, is particularly noteworthy. *Azospirillum* spp. are known to establish associative relationships with non-leguminous crops such as cereals and grasses across diverse agroecological zones (Fani *et al*., 1995). These bacteria contribute to plant growth through multiple mechanisms, including the production of plant hormones such as auxins, N fixation, and phosphate solubilization. They also facilitate siderophore production, which enhances iron availability in the rhizosphere (Bashan *et al*., 2004). *Azospirillum* strains have been isolated from rhizosphere soils and root surfaces of a wide range of crops globally, and several studies have demonstrated their potential to enhance plant growth and yield (Bourscheidt *et al*., 2023; Shime *et al*., 2011; Okon *et al*., 2015).

The successful isolation and identification of *Azospirillum* strains depend heavily on laboratory methodologies. These include the use of selective media and a suite of morphological and physiological tests, such as assessments of colony color, cell morphology, and N-fixation capacity, all of which contribute to identifying and characterizing the microbial diversity present (Han and New, 1998).

Biological N fixation and phytohormone production

Nitrogen fixation and phytohormone production are widely recognized as two of the most critical mechanisms by which PGPR enhance plant development. The efficacy of these processes, particularly the transfer of biologically fixed N from bacteria to plants, is significantly influenced by the compatibility and efficiency of the interaction between specific plant genotypes and bacterial species (Souza *et al*., 2013). Several bacterial genera have been identified and utilized as PGPR, including *Bacillus*, *Pseudomonas*, *Rhizobium*,and *Enterobacter* (Kaur *et al*., 2022).

The microbial conversion of atmospheric N (N_2) into ammonia (NH_3) is a vital ecological process that supports the global N cycle and sustains life by contributing to plant productivity. This transformation is catalyzed by a complex enzyme system known as nitrogenase, which facilitates the reduction of inert N_2 into a bioavailable form for plant uptake (Eady, 1996; Prasad *et al*., 2019).

BNF is carried out by both free-living and symbiotic N-fixing microorganisms. Free-living diazotrophs include cyanobacteria such as *Anabaena* and *Nostoc*,aswell as heterotrophic bacterialike *Azotobacter*, *Beijerinckia*, and *Clostridium*. Symbiotic N fixers include genera such as *Rhizobium*, which forms nodules on the roots of leguminous plants; *Frankia*, which associates with certain non-leguminous dicotyledonous species;and *Azospirillum*, which engages in diazotrophic associative interactions with grasses and other monocots (Vocciante *et al*., 2022).

PGPB Research and Applications in Algeria and North Africa

The agricultural sector in Algeria and other North African countries is challenged by harsh climatic conditions, including drought, high salinity, and poor soil fertility. In response, PGPB have emerged as a promising and sustainable alternative to conventional agricultural inputs. In recent years, Algeria has witnessed growing interest in the study and application of native PGPB to enhance crop productivity and resilience. Several Algerian studies have focused on isolating and characterizing PGPB strains adapted to arid and semi-arid ecosystems. These regions, characterized by high temperatures and low moisture, drive microbial adaptations leading to the production of stress-resilient metabolites (Djinni *et al*., 2019). Targeting rhizospheric bacteria from native desert flora has proven effective in selecting strains capable of enhancing plant tolerance to abiotic stresses such as salinity and drought (Djinni *et al*., 2019; Alsharif *et al*., 2020).

For instance, Bakili *et al*. (2020) demonstrated that endophytic bacteria from plants in saline habitats are a valuable source of salt-tolerant PGPB. Similarly, Dif *et al*. (2022) evaluated five endophytic strains for their growth-promoting effects on tomato under salt stress, with strain ST19 notably mitigating salinity effects. More recently, Benaissa *et al*.(2024) isolated halophilic and halotolerant *Bacillus* strains from date palm rhizospheres, which significantly improved the growth of cowpea plants in saline and arid soils. Beyond growth promotion, PGPB hold considerable promise for biological control of plant pathogens, offering an eco-friendly alternative to chemical pesticides.

In Algeria, numerous studies have highlighted the effectiveness of *Pseudomonas* and *Bacillus* spp. in suppressing phytopathogenic fungi and insect pests (Bensidhoum *et al*., 2016; Mokrani *et al*., 2022). Between 2002 and 2019, researchers identified one new genus and 29 new PGPB species in Algeria, primarily from Saharan soils and palm groves.Among the 50 bioactive compounds characterized, 17were novel antimicrobial metabolites (Djinni *et al*., 2019; Lahoum *et al*., 2019).For example, Aouar *et al*. (2019) reported strong antifungal activity of *Streptomyces* and *Nocardiopsis* isolates against *Fusarium* and *Botrytis*, critical pathogens in tomato and wheat. In northern Algeria, Agrillo *et al*. (2019) demonstrated that *Pseudomonas protegens* reduced fungal infection in tomato, promoting its use in integrated disease management systems.

Several studies have explored the agronomic benefits of PGPB under abiotic stress. Bensidhoum *et al*. (2020) showed that *Pseudomonas* strains improved barley growth, root development, and seed yield under drought stress, emphasizing their application in challenging environments. PGPB, such as *Azospirillum* and *Rhizobium,* have also shown effectiveness in enhancing nutrient availability. Benmati *et al*. (2014) highlighted the role of native *Azospirillum brasilense* in improving N and phosphorus uptake in durum wheat, suggesting further field evaluations. Research across North Africa mirrors Algeria's growing emphasis on microbial solutions to agricultural stress.

In Morocco, *Pseudomonas* strains have shown efficacy in promoting plant growth in saline soils (Madline *et al*., 2021), while additional studies in Morocco and Tunisia confirm the biocontrol potential of PGPB (Ouhaibi-Ben Abdeljalil *et al*., 2016; Ait Rahou *et al*., 2022). These findings support the inclusion of PGPB in integrated pest management systems.In Egypt, biological N fixation by *Azotobacter* and *Azospirillum* has been shown to reduce reliance on synthetic fertilizers and support sustainable agriculture (Nassar *et al*., 2020).

Challenges and Limitations

Despite promising research, several challenges hinder the widespread adoption of PGPB in North African agriculture:

- ✓ *Lack of Awareness*: Many farmers remain unfamiliar with the benefits of PGPB, limiting adoption (Benhammou *et al*., 2022).
- ✓ *Resistance to Change*: Traditional reliance on synthetic fertilizers presents a psychological and practical barrier to adopting biological alternatives.
- ✓ *Environmental Variability*: The diverse soil types and climatic conditions (particularly in arid and semi-arid regions) can affect the performance of PGPB (Mokrani *et al*., 2020).
- ✓ *Policy and Economic Constraints:* Insufficient agricultural policies and lack of economic incentives often deter farmers from integrating new practices (Khalil *et al*., 2022; Mrabet *et al*., 2024).

Prospects and Recommendations

Promoting PGPB-based sustainable agriculture is vital for enhancing productivity, conserving biodiversity, and improving soil and environmental health in North Africa (Jouzi *et al*., 2017). Ben Gaied *et al*. (2024) emphasize that the success of PGPB adoption in arid regions depends on socioeconomic factors and the willingness of farmers to adopt innovative practices. To support this transition:

- ✓ *Raise Awareness and Education*: Training and extension programs should target farmers and agronomists.
- ✓ *Develop Supportive Policies*: Governments must create incentives and infrastructure for biological agriculture.
- ✓ *Encourage Collaborative Research*: Partnerships among government institutions, academia, and the private sector are essential for innovation and technology transfer.

With strategic investments and coordinated efforts, PGPB can play a transformative role in achieving sustainable agricultural development across North Africa.

Conclusion

The integration of PGPB as a sustainable alternative to synthetic N fertilizers holds considerable promise for addressing key agronomic and environmental challenges in North African agriculture. PGPB has demonstrated the capacity to enhance phytohormone production and nutrient acquisition, particularly N and phosphorus availability, improve plant growth under abiotic stress conditions such as salinity and drought, and reduce the ecological footprint associated with conventional agrochemical inputs.

The targeted application of PGPB strains, adapted to local soil and climatic conditions, may increase the efficacy and consistency of these bioinoculants across diverse cropping systems. Such an approach not only contributes to improved soil fertility and crop productivity but also supports broader goals of environmental sustainability and agroecosystem resilience.

However, the widespread implementation of PGPB-based technologies necessitates further multidisciplinary research to elucidate mechanisms of action, optimize formulation and delivery methods, and assess performance under field conditions. Additionally, policy support, farmer awareness programs, and integration into existing agricultural extension frameworks will be critical to facilitate large-scale adoption.

In conclusion, PGPB represents a promising and innovative tool for enhancing the sustainability and productivity of agriculture in North Africa. Their judicious application has the potential to reduce dependency on chemical fertilizers, mitigate environmental impacts, and contribute to the long-term stability of regional food systems in the region.

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