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Halobacteria-Based Biofertilizers in Saline Agroecosystems: Mechanisms of Osmoadaptation, Plant Stress Alleviation and Sustainable Crop Productivity

Nandish Gurubasajar and Thippeswamy Basaiah *

Department of P. G. Studies and Research in Microbiology, Bioscience Complex, Jnanasahyadri, Kuvempu University, Shankaraghatta – 577 451, Karnataka, INDIA.

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Abstract

Oil salinity is a major abiotic stressor that lowers agricultural production globally, affecting about 800 million hectares. In arid and semi-arid regions, poor irrigation practices and high evapotranspiration rates exacerbate salinization. Traditional chemical soil additives and salt-leaching techniques are costly, unsustainable, and environmentally harmful. Microbial biofertilizers, such as halobacteria, have shown great promise for saline agriculture due to their capacity to enhance plant development through nitrogen fixation, phosphate solubilization, and phytohormone synthesis. They also produce siderophores and exopolysaccharides that enhance soil nutrient uptake and structure. They can survive in environments that are inhospitable to the majority of other microorganisms due to their unique osmoadaptation abilities. These traits help plants cope with salt-induced stress by regulating ion homeostasis, boosting antioxidant activity, and fortifying root architecture and water-use efficiency.

The physiological traits of halobacteria, their ways of fostering plant growth in the face of saline stress, and their use as biofertilizers are all examined in this review article. In the face of growing soil salinization and climate change stresses, it emphasizes their potential for sustainable agricultural practices, improving crop production, restoring salt-degraded lands, and guaranteeing food security.

Keywords: Soil salinity; Halobacteria; Microbial biofertilizers; Saline agriculture; Plant growth promotion

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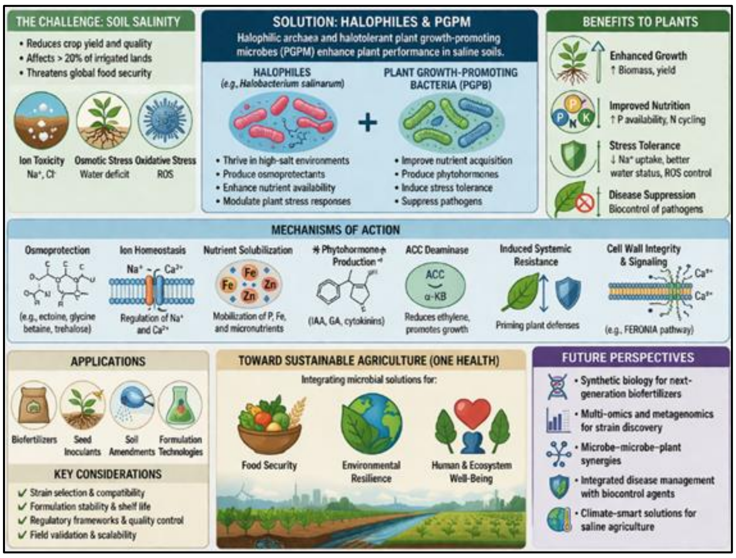
[*] Corresponding author: Thippeswamy Basaiah

Graphical Abstract



1. Introduction

Malnutrition affects 811 million people globally, with a projected 9.7 billion by 2050. This will worsen food security, especially in developing countries. To meet this demand, food production needs to increase by 70% by 2050. However, intensive agricultural practices cause soil degradation due to machinery, drainage, and dewatering, and overuse of manure and fertilizers leads to soil salinization, acidification, and chemical degradation. The growing global food demand and soil degradation are causing a need for sustainable agricultural practices. Soil salinity, affecting 20% of irrigated lands, reduces crop productivity. Conventional chemical fertilizers exacerbate this issue, leading to ecological imbalance. Biofertilizers offer eco-friendly, sustainable solutions to improve soil fertility and crop yield (Garcia et al., 2020).

The increasing demand for agricultural products is causing a decline in cultivated land, soil structure, and natural resource availability. To address this, biotechnological tools like microbial bioinoculants have been developed to provide eco-friendly solutions for food production. Halotolerant bacteria, such as plant-growth-promoting halobacteria (PGPH), are nature-based solutions that promote plant growth in non-saline conditions and improve soil health. These bioinoculants can adapt to high salt concentrations and reduce the use of chemical fertilizers and pesticides, making them an eco-friendly alternative (Egamberdieva et al., 2019).

Halophilic and halotolerant microbes are increasingly being studied for biofertilizer development due to their ability to survive and function in high-salt environments. Halobacteria, found in hypersaline ecosystems, possess remarkable physiological and metabolic traits, making them suitable for saline agriculture and contributing to plant growth.

Recent studies reveal the potential of halobacteria as plant growth-promoting microorganisms (PGPMs) in salt-affected soils. This review consolidates current knowledge on halobacteria-based biofertilizers, examines physiological traits, mechanisms, and role in saline soil management, and highlights advances, application strategies, and challenges in development and field application (Chouhan et al., 2021).

2. Halobacteria: Overview and Characteristics

Halobacterium, a member of the Archaea, can color high salt environments red, like Owens Lake's hyper saline pools, demonstrating its unique metabolic abilities and tolerance to extreme salinity.

2.1. Phylogeny

Halobacterium is an oxymoron, as it is not a bacterium but an archaeon, a member of the Archaea group of prokaryotes. In 1977, Archaea was distinguished from other prokaryotes by the sequence of bases in the 16s ribosome. Most workers now describe Archaea and Eubacteria as two groups of prokaryotes, with Archaea believed to be derived from Eubacteria. Eukaryotes and Archaea are more closely related than eukaryotes and Eubacteria.

2.2. Structure

Archaea cells are rod-shaped, 2-5 um long, with a single lipid bilayer membrane and glycoprotein cell wall. They have distinct phospholipid membranes compared to bacteria and eukaryotes. Halobacterium cells are flagellated and can move towards light sources, particularly yellow-green light at 560 nm.

2.3. Sex and reproduction

Halobacteria, like all prokaryotes, are not sexual but can exchange genetic material through cell division, but do not produce endospores like all Archaeons.

2.4. Matter and energy

Halobacteria are photoheterotrophs, consuming organic compounds to grow and generate ATP. They are autotrophic, making food and consuming some to produce ATP. Regular heterotrophs eat for growth and energy, usually through respiration. When deprived of light, Halobacteria need to eat more to maintain their size and energy needs.

Halobacterium salinarum uses light-activated retinal proteins such as bacteriorhodopsin to pump protons across the membrane and generate a proton gradient for ATP synthesis, and halorhodopsin to drive chloride uptake, helping maintain high intracellular solute levels in hypersaline environments. Members of the haloarchaea, including Halobacterium, are found in hypersaline lakes, salt flats, and solar salterns and require very high salt concentrations often in the range of ~20–30% (w/v) NaCl - for optimal growth (Eichler, 2023).

Halobacteria exhibit key characteristics such as the production of carotenoid pigments for UV protection, light-driven proton pumps like bacteriorhodopsin for ATP synthesis, and adaptation to high-salt environments through compatible solutes or potassium ions. They also produce salt-tolerant enzymes with potential biotechnological applications. These adaptations facilitate survival in extreme conditions and beneficial interactions with plants in saline soils.

3. Impediments to Conventional Agriculture's Sustainability

When applied to agricultural crops, a range of biotic and abiotic stresses can have a detrimental impact on crop yield and food safety. Insect pests, bacteria, viruses, and phytopathogenic fungi are examples of biotic stressors. Abiotic stressors include things like drought, heavy metals, temperature fluctuations, nutrient availability, mineral deficiencies, and soil salinization. All of these stressors significantly impair agricultural lands' fertility and lower global average yields by more than 50% (Etesami et al., 2020). As a result, they pose a genuine ecological and socioeconomic threat to sustainable development by causing major agricultural problems as well as important environmental issues.

3.1. Salinization of Soils

Soil salinization is a common agricultural problem that occurs in various types of land surfaces around the world. Salt-affected lands were defined as land with an electrical conductivity of saturation extract (ECe) greater than 4 dS m^{-1} (Shahid et al., 2013). ECe does not directly measure a specific ion but estimates overall soil salinity due to the presence of various ions, such as Na^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^- and HCO_3^-.Of these ions, sodium and chloride are perceived as the most toxic because of their role as major players in soil structure decline and plant toxicity (Hasegawa et al., 2000). So the identification of the type of affected soil cannot be established only according to ECe. Soil sodicity can be established based on two factors: the concentration of Na^+ ions relative to Ca^{2+} and Mg^{2+} ions, expressed as the sodium adsorption ratio (SAR) and the exchangeable sodium percentage (ESP)

3.2. Diseases Caused by Plants

Phytopathogenic diseases, caused by bacteria, fungi, and viruses, are harmful biotic factors that affect various plant crops. They can cause significant agricultural economic losses and environmental issues worldwide when combined with other biotic and abiotic factors. Fungi and bacteria are responsible for plant infections, affecting all types of plants and colonizing all tissues. They cause symptoms like blasts, spots, blights, rusts, cankers, tissue rots, blights, and mildews. These diseases contribute to hormone imbalances, plant growth disruption, root branching, stunting, and leaf epinasty (John et al., 2021).

Fungi are responsible for various diseases in crop fields and plants, often causing confusion due to their similar symptoms. They also release toxic, hallucinogenic, and carcinogenic substances, such as aflatoxin. Phytopathogenic fungi attack plant organs pre- or post-harvest, with some infecting external or aerial organs and causing visible symptoms. Most fungi are soil-borne and attack the root system, making early symptoms difficult to detect (Ons et al., 2020). Plant pathogenic fungi are divided into three groups: biotrophs, necrotrophs, and hemibiotrophs. Biotrophic fungi survive on living cells and absorb nutrients without causing programmed cell death (PCD). They can cause hyperplasia or hypertrophy of affected organs. Necrotrophs modify host cell plasma membranes and produce PCD before infection and colonization, leading to root rots, trunk rots, trunk infections, post-harvest rots, and tracheomycosis. Necrotrophs cause bark lesions and xylem vascular damage. Hemibiotroph infections start like biotroph infections, requiring living cells to grow, and after development, they adopt necrotrophic pathogen traits and kill their host to feed on dead tissues, causing leaf damage and spot diseases (De Silva et al., 2016).

3.3. Plant Compassion

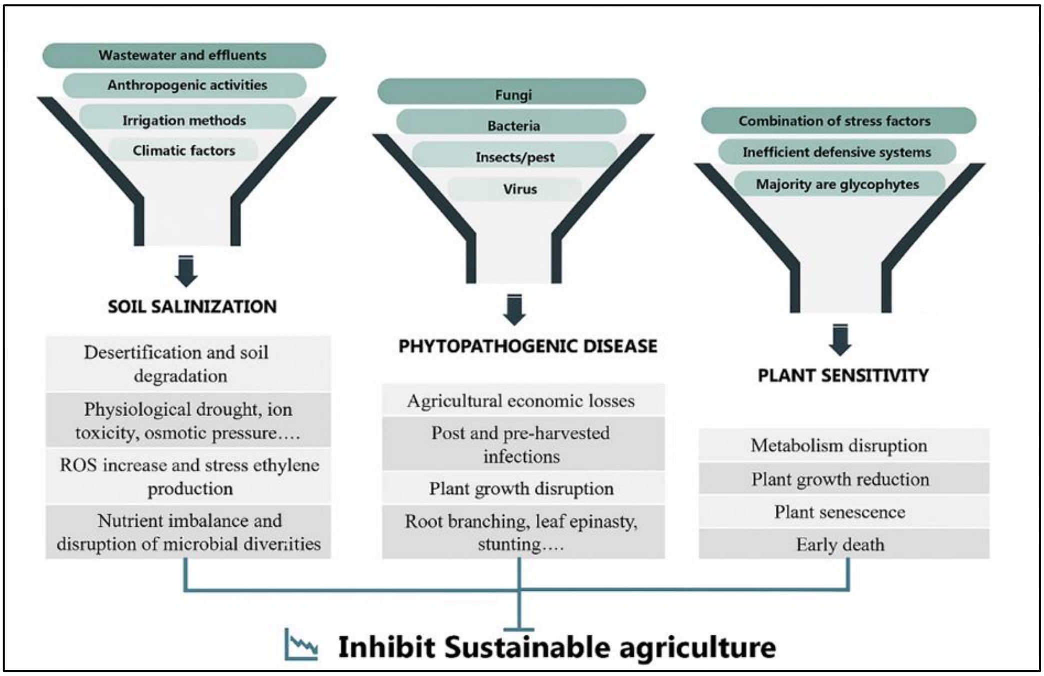


Figure 1 Examples of challenges limiting agriculture sustainability

Changing environmental conditions expose plants to a variety of stressors. Stress can alter a species' or variations physiological metabolism from germination to maturity, lowering growth and crop yield. Plants under stress may produce more ethylene, which could cause senescence and early death. Protein metabolism and hormonal balance may be impacted, as well as growth, seed germination, nutrient intake, and the structure and function of enzymes involved in nucleic acid metabolism (Figure 1). In order to lessen the negative effects of stress, phospholipid membrane degradation, fluidity changes, and damage-associated molecular patterns (DAMPs) can all be brought on by stress (Feng et al., 2018).

4. Mechanisms of Plant Growth Promotion by Halobacteria

Halobacteria contribute to plant growth through both direct and indirect mechanisms:

4.1. Production of Plant Growth Regulators (PGRs)

Halophilic bacteria can produce a variety of **plant growth regulators** that help promote plant growth, even under stress conditions like salinity (Kumar et al., 2023).

- **Indole-3-acetic acid (IAA)**: This is a type of auxin that enhances root elongation and can stimulate lateral root development. In saline soils, where plants may struggle to establish roots, IAA production by halophilic bacteria helps promote better root growth and nutrient uptake.
- **Cytokines and Gibberellins**: These hormones help with shoot development, cell division, and overall plant growth. Cytokines are particularly useful in promoting cell division, while gibberellins can influence stem elongation and overall plant height.
- **Example Mechanism**: *Halobacterium salinarum* produces IAA, which can help wheat and other crops grow better in saline soils by improving root growth and nutrient absorption.

4.2. Salt Stress Mitigation

Halophilic bacteria are naturally adapted to high-salt environments. When introduced to plants under saline stress, these bacteria help the plants mitigate salt-induced damage by improving their tolerance mechanisms.

- **Osmotic Regulation**: Halophilic bacteria produce compatible solutes (e.g., **glycerol**, **trehalose**, and **ectoine**) that help maintain osmotic balance inside plant cells. These solutes protect plant cells from dehydration and cellular damage due to excess salts.
- **Antioxidant Production**: Salt stress often leads to the production of reactive oxygen species (ROS), which can damage plant tissues. Halophilic bacteria can stimulate the plant's antioxidant systems (e.g., **superoxide dismutase**, **peroxidase**, and **catalase**) to neutralize ROS and protect the plant from oxidative damage (Kumar et al., 2023).
- **Example Mechanism**: *Salinivibrio* species produce **ectoine**, which not only helps them survive in saline conditions but also protects plants from salt-induced oxidative stress.

4.3. Nutrient Availability and Solubilization

Many halophilic bacteria can enhance **nutrient availability** by solubilizing minerals, especially in nutrient-deficient soils, which is crucial for plants grown in saline environments where nutrient uptake is often limited.

- **Phosphate Solubilization:** Phosphorus is often bound to soil particles and becomes less available to plants, particularly in alkaline or saline soils. Halophilic bacteria can solubilize phosphate, making it more accessible to plants.
- **Nitrogen Fixation:** Some halophilic bacteria can fix atmospheric nitrogen, converting it into a form that plants can use. This can be especially beneficial in saline soils where the availability of nitrogen is limited (Kumar et al., 2023).
- **Example Mechanism**: *Bacillus* and *Pseudomonas* species have been shown to solubilize phosphate and other nutrients, enhancing plant growth in saline conditions.

4.4. Exopolysaccharide (EPS) Production

Halophilic bacteria produce **exopolysaccharides (EPS)**, which play an important role in soil structure and plant growth.

- **Water Retention**: EPS helps to improve the soil's water-holding capacity, which is vital in arid and saline environments where water availability is limited.
- **Soil Aggregation**: EPS can help bind soil particles together, improving soil structure and root penetration. This leads to enhanced root growth and stability, allowing plants to access more nutrients and water.
- **Example Mechanism**: *Halomonas* species produce EPS that improves water retention in soils, which is crucial for plant survival in water-scarce or saline environments (Goszcz et al., 2025).

4.5. Bio control Activity

Halophilic bacteria can also act as bio control agents, suppressing plant pathogens and promoting plant health.

- **Antimicrobial Compounds**: Some halophilic bacteria produce antimicrobial compounds such as bacteriocins, hydrogen peroxide, and antifungal metabolites. These compounds help to protect plants from root pathogens, fungal infections, and other harmful microbes in the rhizosphere.
- **Pathogen Suppression**: By inhibiting the growth of plant pathogens (e.g., *Fusarium* spp., *Rhizoctonia* spp.), halophilic bacteria can help maintain plant health and improve overall growth in stressed environments.
- **Example Mechanism**: *Bacillus* and *Pseudomonas* species produce antifungal compounds that can protect crops like tomatoes and rice from root rot diseases caused by soil-borne pathogens (Meinzer et al., 2023).

4.6. Rhizosphere Colonization and Biofilm Formation

Halophilic bacteria can colonize the plant rhizosphere (root zone), creating a microbial community that supports plant growth.

- **Biofilm Formation**: In saline conditions, halophilic bacteria form biofilms that protect the plant's roots from pathogens and help in nutrient absorption. Biofilms also provide a physical barrier against soil salinity, helping plants maintain their health.

- **Enhancing Root Growth**: The biofilm can also promote the development of root hairs, improving the surface area for nutrient absorption and water uptake.
- **Example Mechanism**: *Bacillus* and *Staphylococcus* species are capable of forming biofilms that enhance root growth and provide a protective layer against both biotic and abiotic stresses (Dragojevic et al., 2024).

3.7. Impact on Soil Health and Microbial Community Dynamics

Halophilic bacteria also affect the overall health of the soil by interacting with other soil microbes.

- **Microbial Consortia**: By interacting with other beneficial soil microorganisms, halophilic bacteria can enhance microbial diversity and stability, which improves overall soil fertility and plant health.
- **Improved Soil Structure**: As discussed with EPS production, halophilic bacteria can help to form aggregates that improve the soil's structure, enhancing root penetration and water infiltration (Kumar et al., 2023).

5. Role in Saline Soil Reclamation

Halobacteria can significantly rehabilitate saline soils by improving soil structure through extracellular polymeric substances (EPS) that enhance aggregation and porosity, and by reducing ion toxicity by sequestering excess sodium ions. Additionally, they contribute to microbial restoration, boosting diversity and resilience in degraded soils, particularly in extreme salinity, outperforming traditional plant growth-promoting microbes (PGPMs) in salt-affected regions.

6. Halobacteria and Plant-Microbe Interactions

Halobacteria interact with plants primarily through the rhizosphere but may also colonize root tissues as endophytes. These interactions are often crop-specific and influenced by environmental conditions.

Positive growth responses in crops have been noted, including enhanced root growth and salinity tolerance in rice (*Oryza sativa*), improved biomass and grain yield under salt stress in wheat (*Triticum aestivum*), and reduced oxidative damage in tomato (*Solanum lycopersicum*) leading to better fruiting. Co-inoculation of Halobacteria with beneficial microbes like mycorrhizal fungi or rhizobia can enhance the efficacy of biofertilizers in saline soils.

7. Formulation and Application of Halobacteria-Based Biofertilizers

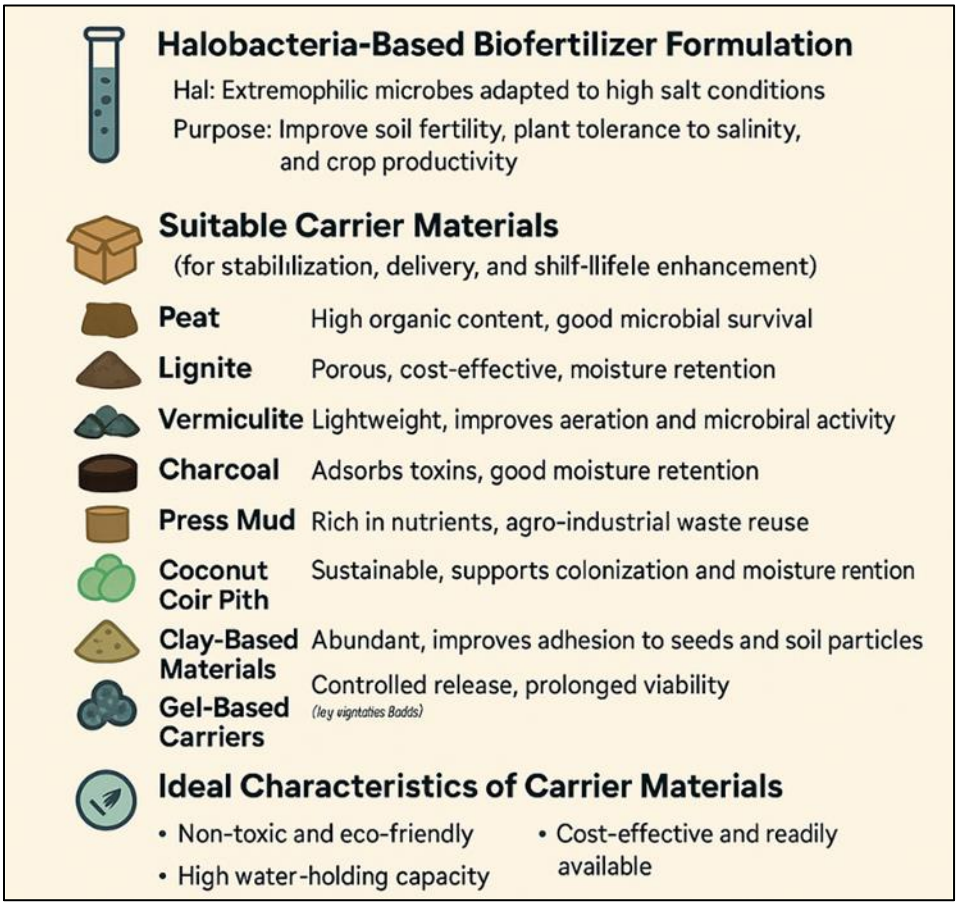
Developing a viable biofertilizer requires stable, effective, and easy-to-apply formulations.

7.1. Isolation and Cultivation

Halobacteria are cultured using high-salt media (15–25% NaCl), often requiring specific pH and temperature conditions.

7.2. Carrier Materials

Halobacteria-based biofertilizers are getting a lot of attention because they can grow in very salty environments and help plants grow even when they are under stress. These extremophilic microorganisms, which are part of the Archaea domain, can make soil more fertile, help plants take in more nutrients, and make crops more resistant, especially in soils that have a lot of salt. It is important to use the right carrier materials to make sure that they are stable, viable, and can be delivered to the field quickly. Carrier materials are substances that support halobacteria by shielding them from environmental stress, keeping their metabolism going, and making it easy to apply them to seeds or soil. The best carriers should be safe for people and the environment, cheap, and able to hold moisture to help microbes live for a long time. Peat, lignite, vermiculite, charcoal, press mud, coconut coir pith, clay-based materials, and gel-based systems like alginate are all common carrier materials (Figure 2).



Halobacteria-Based Biofertilizer Formulation

Hal: Extremophilic microbes adapted to high salt conditions

Purpose: Improve soil fertility, plant tolerance to salinity, and crop productivity

Suitable Carrier Materials

(for stabililization, delivery, and shilf-llifele enhancement)

Peat	High organic content, good microbial survival
Lignite	Porous, cost-effective, moisture retention
Vermiculite	Lightweight, improves aeration and microbiral activity
Charcoal	Adsorbs toxins, good moisture retention
Press Mud	Rich in nutrients, agro-industrial waste reuse
Coconut Coir Pith	Sustainable, supports colonization and moisture rention
Clay-Based Materials	Abundant, improves adhesion to seeds and soil particles
Gel-Based Carriers	Controlled release, prolonged viability (ley vigntaties Bodds)

Ideal Characteristics of Carrier Materials

- Non-toxic and eco-friendly
- High water-holding capacity
- Cost-effective and readily available

Figure 2 Carrier Materials used for Halobacteria-based biofertilizers

Vermiculite and coconut coir enhance aeration and microbial activity, while peat and lignite provide high organic content and moisture retention. Press mud offers nutrients and recycles waste, and charcoal absorbs moisture and toxins. Clay-based carriers aid in seed adhesion and microbial protection, while gel carriers enable slow seed content release. These materials can be utilized in various forms - powders, pellets, liquids, or encapsulations—depending on their application, such as seed coating or soil amendment. Selecting appropriate carrier materials is crucial for optimizing Halobacteria-based biofertilizers, thereby supporting sustainable agriculture in challenging environments.

7.3. Delivery Methods

7.3.1. Seed Coating

Seed coating is a widely used agricultural practice in which seeds are covered with external materials to improve their physical properties and functional performance. This process enhances seed appearance, size, and weight, making them easier to handle and sow, while also serving as an efficient method for delivering beneficial substances. These include plant growth regulators, essential micronutrients, and microbial inoculants that help protect seeds from pathogens and support early plant development.

The practice of seed coating dates back to the 1930s, initially applied to cereal crops, and became commercially established during the 1960s. Today, it is extensively adopted across horticultural and field crop production systems worldwide. Modern seed coatings commonly incorporate colouring agents and tracers, such as fluorescent dyes, to aid identification, along with protective compounds like pesticides and soil conditioners that improve moisture retention. In addition, growth-promoting substances such as salicylic acid and gibberellic acid are often included to enhance germination and seedling vigor.

A significant advancement in this technology is the incorporation of Plant Beneficial Microbes (PBMs) into seed coatings. This approach enables the targeted delivery of small quantities of microbial inoculum directly to the seed–soil interface, ensuring their presence during germination and early growth stages. As a result, coated seeds establish more effectively, leading to healthier plants and improved crop productivity.

7.3.2. Soil drenching

In Soil drenching method, the fungicides were mixed with water and about the same concentration as spraying and applied to the soil surface either before or after plants emerge. The required quantity of fungicide suspension is applied with a sprinkler or rose can per unit area so that the fungicide reaches a depth of at least 10-15 cm. This method is followed for controlling damping off. Root rots or infections at the ground level (Table 1).

Table 1 Important fungicides used for soil drenching

Fungicide Dosage (%)	**Pathogens controlled:**
Bordeaux mixture 1 %	*Pythium, Phytophthora*
Cheshunt compound 0.3 %	*Pythium*, *Sclerotium*.
Copper oxy chloride 0.2 to 0.3 %	*Pythium*, *Phytophthora*
Captan 0.2 to 0.3%	*Pythium*, *Phytophthora*
Captafol 0.3 %	*Macrophomina*, *Pythium*, *Rhizoctonia*, *Phytophthora*

Quantity of fungicidal solution required for soil drenching:

- For Mini plots or shallow flats: 2.5 L/m^2
- Pots up to 40 cm size and propagative beds up to 10 cm in depth: 3.0 L/ m^2
- Pots and propagative beds greater than 10 cm in diameter or depth: 3.5 to 6.0 L/ m^2

7.3.3. Foliar Spray method

The foliar spray method involves applying nutrients, growth-promoting substances, protective chemicals, or beneficial microorganisms directly onto plant leaves as a fine mist. In this approach, plants absorb the applied materials through the leaf surface, primarily via stomata and the cuticular layer, resulting in quick assimilation and faster physiological effects compared to soil application.

This method is especially useful for supplying micronutrients, as it avoids problems related to soil nutrient fixation, poor availability, or nutrient losses. Foliar spraying is also widely used for applying plant growth regulators and biostimulants that enhance plant growth, improve stress tolerance, and support overall plant health. Additionally, it serves as an effective means of protecting crops from pests and diseases by delivering control agents directly to the target tissues.

In recent years, foliar application has been explored for delivering plant-beneficial microorganisms. When applied under favourable environmental conditions, these microbes can survive on leaf surfaces and interact with the plant, contributing to improved growth and resilience. The foliar spray method ensures uniform coverage, accurate dosing, and reduced input requirements, making it an efficient and economical strategy in modern crop management systems.

7.4. Shelf-Life and Storage Stability

For the commercial use of halobacteria-based biofertilizers, preservation of microbial viability during storage is a key determinant of product quality and effectiveness. In general, an acceptable formulation should maintain adequate cell viability for 6–12 months under variable environmental conditions, including changes in temperature and relative humidity. Unlike conventional biofertilizer microorganisms, halobacteria are extremophiles that require high salinity for survival, which presents additional challenges for formulation and storage (Ventosa et al., 2015).

One of the major constraints affecting shelf life is limited tolerance to desiccation. Reduced moisture content, particularly in solid carrier-based formulations, can lead to a rapid decline in viable cell counts. To address this issue, recent studies have focused on the use of osmoprotectants, compatible solutes, and salt-based stabilizing agents, which help maintain membrane stability and protect enzymatic functions during storage (Oren, 2013). Incorporation of salts such as sodium chloride or potassium chloride at optimized concentrations has been reported to reduce osmotic stress and enhance cell recovery after rehydration (DasSarma & DasSarma, 2017).

Advanced formulation approaches, including encapsulation in alginate matrices, polymer-based coatings, and liquid formulations buffered with saline solutions, have shown promise in improving storage stability and ease of field application (Bashan et al., 2014). Nevertheless, the absence of standardized storage and shelf-life evaluation protocols for halobacteria-based products remains a significant gap, emphasizing the need for further research in formulation technology.

8. Case Studies and Experimental Evidence

An increasing number of studies highlight the potential of halobacteria as plant growth–promoting microorganisms, particularly under saline and sodic soil conditions. Experimental evidence from laboratory, greenhouse, and limited field trials indicates their positive influence on plant growth, nutrient acquisition, and tolerance to salinity stress (El-Gendy et al, 2022, Cheng et al, 2021). Field-based evidence, although limited, further supports these findings. A pilot study conducted in salt-affected paddy fields of Gujarat, India, recorded a 20–30% increase in grain yield in plots treated with halobacterial biofertilizers compared to untreated controls. Improved root architecture, higher chlorophyll content, and increased microbial activity in the rhizosphere were identified as contributing factors. Despite these encouraging outcomes, most available data originate from controlled or small-scale trials, and large, multi-season field evaluations are still scarce (Singh & Jha, 2016).

9. Challenges and Limitations

9.1. Cultivation Complexity

A major limitation in the large-scale use of halobacteria as biofertilizers is their strict requirement for high-salt growth conditions, often ranging from 2 to 4 M NaCl. Such conditions complicate fermentation processes, increase production costs, and require specialized equipment and corrosion-resistant materials (Oren, 2013). In addition, maintaining aseptic conditions and preventing contamination in hypersaline media during industrial-scale production remains technically challenging.

9.2. Regulatory Hurdles

Halobacteria belong to the domain Archaea, which are frequently excluded from existing biofertilizer regulatory frameworks that mainly address bacteria and fungi. In several countries, including India, the lack of clear guidelines for archaea-based products creates regulatory uncertainty, slowing down product approval and commercialization (Malik et al., 2020). The absence of standardized quality control parameters further limits market entry.

9.3. Field Variability

The performance of halobacteria-based biofertilizers under field conditions can vary considerably depending on soil characteristics, salinity intensity, climatic factors, irrigation practices, and crop genotype. Such variability reflects the lack of standardized recommendations regarding dosage, application timing, and delivery methods (e.g., seed treatment, soil application, or foliar spray). Consequently, extensive multi-location trials are required to establish consistent and reliable application protocols.

9.4. Knowledge Gaps

Despite growing interest, the mechanisms governing halobacteria–plant interactions remain poorly understood. Information on root colonization processes, signaling pathways, and long-term impacts on native soil microbial communities is limited. Moreover, the ecological behavior of halobacteria in non-saline or moderately saline soils and their long-term persistence require careful investigation before large-scale adoption (Ventosa et al., 2015).

10. Future Prospects and Research Directions

10.1. Genomic and Proteomic Insights

Recent advances in genomics, transcriptomics, and proteomics provide valuable tools for identifying genes and metabolic pathways associated with plant growth promotion, stress tolerance, and nutrient mobilization in halobacteria. Such insights can support the selection and development of efficient strains for agricultural applications (DasSarma et al., 2020).

10.2. Genetic Engineering and Synthetic Biology

The application of synthetic biology and genetic engineering offers new opportunities to enhance halobacterial performance. Traits such as nitrogen fixation, increased indole-3-acetic acid (IAA) synthesis, and improved phosphate solubilization could be introduced or optimized. However, biosafety concerns and regulatory acceptance must be carefully addressed before deploying genetically modified strains (Singh et al., 2022).

10.3. Field Trials and Scale-Up

Future research efforts should focus on large-scale, multi-location field trials across different agro-climatic zones to validate laboratory and greenhouse results. Optimization of carrier materials, formulation strategies and delivery systems will be essential for successful commercialization and farmer acceptance.

10.4. Policy Development and Farmer Awareness

The formulation of clear regulatory guidelines for archaea-based biofertilizers is crucial to facilitate commercialization. In parallel, awareness programs and extension activities are needed to educate farmers about the benefits and appropriate use of halobacterial inoculants, particularly in salt-affected regions. Integration of these biofertilizers into sustainable agriculture practices may contribute to soil health restoration and climate-resilient crop production.

11. Conclusion

Halobacteria present a novel and promising solution to the challenges posed by saline soils in agriculture. Their extreme halotolerance, plant growth-promoting potential, and biotechnological adaptability position them as ideal candidates for next-generation biofertilizers. However, transitioning from lab to land requires overcoming scientific, regulatory, and socio-economic hurdles. Continued interdisciplinary research, coupled with policy support and field validation, will pave the way for integrating halobacteria-based biofertilizers into sustainable agricultural practices.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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