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Molecular Signalling Involved in Microbial Siderophore-Producing Bacteria Assisted Improvement of Micronutrient Availability and Crop Productivity in Saline/Alkaline Soils

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ABSTRACT
Iron is an essential plant nutrient that is not replaceable with any other macro or micronutrient. In alkaline and saline soil plant growth is limited due to poor nutrient availability as iron is also present in its insoluble Fe^{+3} oxidation state. Certain microorganisms produce small metal (iron) chelating agents called siderophores that bind iron/other metals, thereby enhancing their availability. Considering the need for enhancing the bioavailability of immobilized nutrients in stressed soil with the help of siderophore and other plant growth-promoting mechanisms shown by microorganisms. Hence, the aim of this review article is mainly focused on the general information related to siderophore, and its types (catecholate, hydroxymate, carboxylate, and mixed ligand siderophore) and their structural differences, mechanism of transport of iron across the membrane by siderophores, molecular signaling, and genes involved in biosynthesis and their application for humans to making a better world.
Keywords: *Alkaline/ saline soil; iron chelation, siderophore; molecular mechanism.*

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INTRODUCTION

Soil salinization and alkalization are the most serious global environmental problems and arising threats to crop productivity. The cultivated land, which is affected by salt may cause an adverse effect and oxidative damage to the soil as a result growth, nutrient uptake by plants, and their metabolic & photosynthetic activities are reduced. Agriculture is the largest private enterprise in India but the present population growth rate together with diversions of fertile land for non-agriculture uses exerts tremendous pressure on agriculture. Due to continual agricultural operations and incorrect waste disposal (chemical wastes, industrial wastes, nuclear wastes, etc.), undesirable changes occur in soil, generating soil pollution and resulting in salinization/alkalization of soil, which is the second most important factor of soil degradation. Out of the total geographical area (329 Mha) of land in the world, 175 Mha area is considered a salt-affected area in which alkaline and saline soils account for 3.6Mha and 5.5 Mha respectively. It is estimated that 1.5 billion land worldwide is salt-affected [1]. Salt-affected areas are one of the most important degraded areas where soil productivity is reduced due to either salinization (EC > 4dS/m) or sodicity i.e. exchangeable sodium percentage(ESP > 50) or both. When the pH of the soil exceeds 7.0, the availability of micronutrients such as manganese, iron, copper-boron, and zinc decreases due to the formation of low solubility compounds, increased retention by soil colloids (clay and organic matter), and the conversion of soluble forms into fixed (insoluble) forms that plants cannot absorb [2]. Thus, nutrient availability becomes the main limiting factor for plant growth in such stressed soils. To overcome nutrient deficiency and increase agricultural productivity, large amount of chemical fertilizer are added to the soil, but nearly 70% of it becomes fixed and unavailable to plants [3]. As a result, it is critical to shift toward the employment of halo-alkalo-tolerant soil microorganisms with plant growth-boosting properties for reclamation and enhancing nutrient bioavailability in place of/as an alternative to chemical fertilizers. Several rhizosphere-competent bacteria are known to stimulate plant growth by creating various growth-promoting properties such as micro- and macronutrient solubilization, siderophore production, ACC deaminase production, nitrogen

fixation, and so on [4]. Iron is a key micronutrient that modulates bacteria's surface motility and also plays a vital role in biofilm formation. Despite being one of the most abundant elements in the earth's crust, it has a low bioavailability. Alkaline and calcareous soils are thought to be the primary causes of iron deficiency in plants; despite the high iron content of the soil, the accessible Fe concentration is below the recommended level for plant growth, i.e. 10^{-9} to 10^{-4} M [5]. Metal chelating agents, such as siderophores, are being studied as a remedy for reclaiming alkaline and calcareous soils.

SALINE/ALKALINE SOIL: EXISTING SCENARIO AND NUTRIENT STATUS

Distribution of saline/ alkaline soil in India

India has 2.4 % area of the total world's area which supports about 16.7 %`of the total world's population and only 49.2 % (162Mha) area is arable. In India, alkaline/salt-affected soils are mainly found in the states of Madhya Pradesh, Andhra Pradesh, Karnataka, Rajasthan, West Bengal, Tamil Nadu, and Gujarat, which cover about 6.74 million ha of land (Fig 1). According to a report, the salinization of agricultural land will damage roughly 30% of cultivable land within the next 25 years (up to 50% of land degradation), and the problem will worsen by 2050 [6]. Because of the implementation of irrigation in new regions, salinized areas in India continue to grow yearly and the annual speed of increment is around 10%.

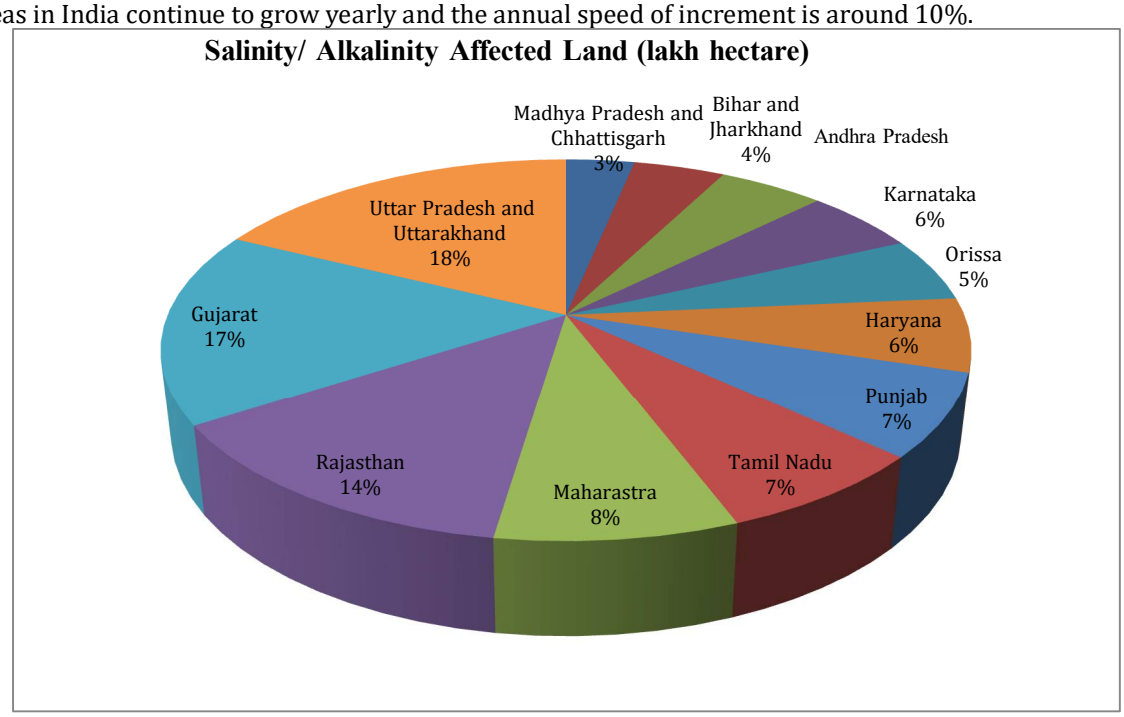


Fig 1 Graphical representation of saline/alkaline affected land in India.

General classification of salt-affected soil

In saline soil, the concentration of soluble salt is in excess due to the presence of sulphates, chlorides and carbonates of sodium, calcium and magnesium while alkaline soils are rich in sodium carbonate [7]. Salt-affected soils are classified into three types: (i) saline soil, which contains a huge concentration of soluble salts like calcium, magnesium, potassium etc. (ii) sodic soil in which sodium is the dominating species and (iii) sodic-saline soil in which there is high salt concentration as well as high sodium content. In general, there are two types of salt-affected soils: (i) saline soils that show high electrical conductivity (>4 dS m^{-1}) but low sodium content, and (ii) sodic soils that have high electrical conductivity (>4 dS m^{-1}) and high sodium content [8].

Nutrient status saline/alkaline soil

The high concentration of certain ions such as calcium, chloride, magnesium, sodium, sulphate etc. causes the soil salinity thereby degrading the soil structure also. Salinity affects the arid or semi-arid regions and its deposition around the rooting zone decreased productivity, nutrient uptake [9] and affects plant water intake due to high osmotic pressure [10]. Effect of soil alkalinity is more fatal, it reduces uptake of calcium ions, breakdown the soil structure etc. The excess salinity in soil water results in plant available water and plant stress [11]. More than 6% of total world agricultural lands are on the edge of disappearing because of salt stress [10]. In alkaline soil, as calcium (Ca^{2+}) ions are abundant, tri-calcium phosphate (TCP) is the most common fixed form of phosphorus, likewise in acidic soil, ferric phosphate ($FePO_4$) and aluminum

phosphate ($AlPO_4$) are the more profuse inorganic phosphorus forms. As a result, the concentration of soluble P in the soil is minimum and thus, unavailable to plants.

IRON IS AN IMPORTANT PLANT NUTRIENT

Iron is the fourth most abundant vital element in Earth's crust required for all the living life forms and it plays an important role in host-bacteria interactions [12]. Iron is known to be a central component of the chainof electrons as well as a co-factor of several enzymes. It is important for various metabolic activities, acting as the major element in respiratory (TCA), photosynthesis (ETS), co-factor for enzymes (e.g. nitrogenase, catalase, etc.), synthesis of chlorophyll and other pigments. It is also important for the formation of biofilm as it regulates surface motility and stabilizes the polysaccharide matrix [13]. In plants, iron deficiency caused iron chlorosis (interveinal chlorosis) [14]. Iron chlorosis is very common all over the world, especially in semi-arid and arid regions, although there is an abundant amount of iron present in the soil but is not available for many plant species because of the existence of calcium carbonate, phosphate and other factors in soil that fix and limits its availability. The soluble oxidation state of iron i.e. (Fe^{2+}) is not stable under aerobic conditions and at physiological pH (7.0), so it is converted into Fe^{3+} oxidation state and forms insoluble hydroxide and oxyhydroxide precipitates [15] and reduces its availability. Iron hydroxide and oxides are responsible for the reddish and yellowish color of soil [16]. In acidic soil, if microbial activities are adequate to decrease the oxygen supply, some ferric ionswill be transformed into soluble ferrous forms. While in alkaline or calcareous soil, rapid microbial respiration leads to high carbon dioxide concentration in soil that may react with water which forms bicarbonate ions. Plants absorb these ions, which immobilize iron within the plants resulting in a deficiency. Alkaline and calcareous soils are considered the main inducers of iron deficiency in plants; the available iron concentration is below the optimum level for the plant [17]. Once inside, iron forms complex with chelators and distributed to sink tissues where it is used predominantly in the production of enzyme cofactors or components of electron transport chain [18]. The distribution of species of plant in natural ecosystems limits the yield and nutritional quality of crops indicating the availability of iron in soil.

MICROBIALLY INDUCED NUTRIENT ALLEVIATION

Soil reclamation using beneficial microbes

Different strategies have been developed to overcome thissodic/alkaline stress, such as the development of salt-tolerant crop plants, but the use of microorganisms to withstand this unhealthy environment is a more reliable measure to be taken[19].Plant nutrient uptake is influenced by the architecture of the root, proton efflux from the roots release phytometallophore which increase the solubility of nutrients i.e. (Ca,Mg, Fe, Co, Zn and Mn) for plant. These phytometallophores are stable chelates so they extract the ions from calcareous soil (deficiency of these metals is common in calcareous and non-calcareous soil [20]. Many moderate salt tolerant rhizobia (e.g., *Sinorhizobium arboris*) have been isolated from Acacia, which can withstand 2%-3%NaCl concentration. Many bacterial strains such as *Chryseobacterium balustinum*, have been reported to enhance plant growth in saline stress conditions- by enhancing thenitrogen- fixation rate, root surface area and germination rate. Reclamation is a common practice to reduce runoff and erosion in sodic soils. Recovery of sodic soils includes the replacement of exchangeable Na with Ca ions[21].

Microbial ionophores and plant growth promotion

Plant growth-promoting rhizobacteria (PGPR) have gained widespread acceptability and relevance in agriculture over the last several decades due to the use of various modes of action that allow for increased crop output [22].The term PGPR was firstly used by Kloepper, (1970) [23]. Plant growth-promoting rhizobacteria (PGPR) are the rhizosphere bacteria that enhance plant growth by a variety of mechanisms like phosphate solubilization, siderophore production, biological nitrogen fixation, rhizosphere engineering, production of 1-Aminocyclopropane-1-carboxylate deaminase (ACC), quorum sensing (QS) signal interference and inhibition of biofilm formation, production of phytohormone, exhibiting antifungal activity, production of volatile organic compounds (VOCs), induction of systemic resistance, promotion of beneficial plant-microbe symbioses, interference with pathogen toxin production etc[24]. There are many alkalo-halo tolerant plant growth promontory microorganisms such as Pseudomonas, Trichoderma, Rhizobium, Bacillus, and Thiobacillus which can increase plant growth under saline/alkaline stress conditions [25]. Plant growth promoting microbes (PGPM) are sustainable plant growth enhancers and have the potential to aid with the variety of stresses in their environment. Considering the long-term evolutionary relationships between plants and microbes, it is probably that much remains unknown about the potential benefits of microbes that could be harnessed from PGPM [26].The use of PGPR in agribusiness began in the 1950s and is utilized commercially in form of biofertilizers and biopesticides [27]. Salt tolerant endophytic bacteria are reported to promote plant growth indirectly or directly by the production of phytohormone, biocontrol of host plant disease and by improving its nutritional status. Endophytic bacteria can improve the health of the plant by targeting pests and pathogens with antibiotics, hydrolytic enzymes,

nutrient limitation, as well as by priming plant defenses [28]. Some halotolerant bacteria possess the capacity to solubilize phosphates [29]. Bacillus species significantly increase the stomatal conduction in Glomus species under saline conditions [30]. Zhao et al., [31] reported the growth-promoting potential of Trichoderma sp. under saline stress, by providing ferrous ion availability to cucumber via siderophore production. Trichoderma sp. also shows contradictory activity against Sclerotium rolfsii under saline stress [32]. Various genera of salt-tolerant plant growth-promoting rhizobacteria (STPGPR) have been isolated from highly alkaline, saline and acidic soils. Many of them are also known to alleviate various biotic and abiotic stresses in plants [33]. Due to increasing soil acidity and salinity, increasing metal toxicity in soil, abiotic stress, drought, heat, and soil deterioration affect plant growth and severely limit crop production. Several studies point to the useful microbes, especially plant growth-promoting rhizobacteria (PGPR), which play a significant role in helping the plants in overcoming stresses and retain their productivity [34].

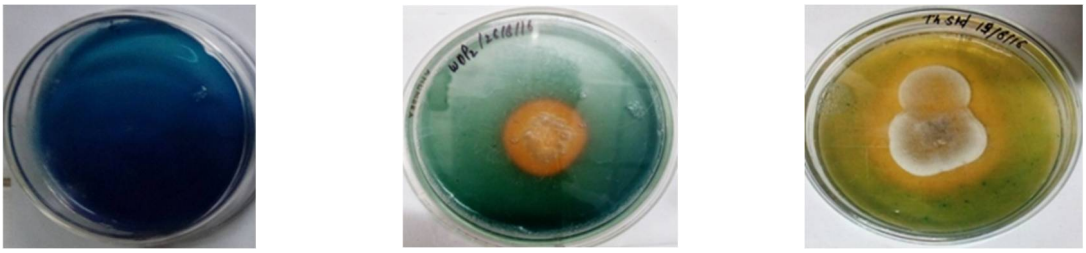
SYNTHESIS OF MICROBIAL IONOPHORES (SIDEROPHORE) IN RESPONSE TO IRON STRESS

There are different ways to produce siderophores by bacteria, fungi and plants.The aerated atmosphere of the earth results in the surface iron becoming converted to oxyhydroxide polymers that are very sparingly soluble. The concentration of free ferric ions at neutral pH is dependent on the solubility product constant of ferric hydroxide. Microorganisms growing under aerobic conditions need iron for a variety of functions like in reduction of oxygen to produce ATP, the reduction of ribonucleotide precursors of DNA, the formation of heme, and other vital purposes. However, in reference to micronutrient uptake by PGPM, most of the research has been carried out on two elements: Fe and zinc (Zn). Almost one-third soil of the earth can be considered Fe deficient [35]. Concerned by the pathways of microbial siderophores biosynthesis, they are primarily contingent on non-ribosomal peptide synthetase [36]. In Fe-starved conditions, siderophores produced by rhizospheric microbes play an important role in plant health management [37]. Along with growth promotion in crop plants siderophore also helps in controlling phytopathogens and diminishing the toxic effects of heavy metals in soil [38]. Pseudomonads [39], Bacillus spp. [40], Azotobacter spp. [41], Acinetobacter spp., and Rhizobium spp. are known as siderophore-producing plant growth promoting rhizobacteria efficiently. According to Rawatet al., (2011) [42], a siderophore produced by Trichoderma sp. combats the detrimental effects of abiotic stress on the plant. Prabhavati and Mallaiah, [43] reported that the production of siderophore in Rhizobium strains increases with an increase in the salt concentration with respect to control (without salt), and the maximum production of siderophore was shown by strains HGR5 and HGR8 (90µg/mL) at 600mM salt concentration. Deshwal and Kumar, [44] reported that the Pseudomonas strain shows optimum siderophore production at 1% NaCl concentration and with an increase in the NaCl concentration siderophore production is delayed. Pseudomonas fluorescence NT1 strain showed maximum siderophore production at 6% NaCl concentration after 72h of incubation i.e. (1000µg/mL) [45]. The biosynthesis of siderophore by Streptomyces isolates are increased in the presence of NaCl and the highest production of siderophore was observed in 300 Mm NaCl. The effect of pH on siderophore production was observed on A.oryzae[46]. The maximum siderophore production was observed at pH 7.0 followed by pH 8.0, i.e., 54.47% gradual decrease was observed below pH 7.0 and above pH 7.0. For all isolates, production of siderophores occurred when the value of pH exceeds 7.5, it was also determined that siderophores produced by the isolate were capable of binding with Fe^{3+}, Ga^{3+} and Al^{3+}ions [47]. McMillan et al., [48] reported an alkaliphilic Bacillus sp. having optimum pH greater than 9.0 for growth and siderophore production. The alkaliphilic siderophores contain hydroxamate and catecholate moieties and its synthesis was suppressed with the addition of $FeCl_3$ and stimulated by manganese (II) addition. Figueroa [49] checked siderophore production in Halomonas sp. SL01 under alkaline pH ranging from (8-11), the Halomonas sp. SL01 showed siderophore production upto pH 11 and maximum siderophore production (40µM) was shown at pH 9. *Azotobacter vinelandii*, B. megaterium and B. subtilis are known to be the bacterium with the simplest performance since the individual medium filtrate had the flexibility to advance iron expeditiously at hydrogen ion concentration 9.0 with the best iron complexation capability[50].

Role of siderophores in nutrient acquisition

The first reported siderophore was isolated from Ustilago *sphaerogena* [51]. These are iron-chelating low molecular weight compounds (<10 KD) [52]. It chelates free iron and forms a complex which is transported into the cell via membrane receptor protein molecules. These protein molecules are encoded by five genes in the operon and turned off when an adequate amount of iron has been taken into the cell [53, 54]. In Gram-positive bacteria, transport of siderophore iron complex is by the involvement of siderophore irrevocable proteins, ATPases and permeases, while in Gram-negative bacteria siderophore iron complex is transferred through a periplasmic binding protein and cytoplasmic membrane protein corresponding to ATP binding cassette transfer. Siderophore-producing organisms act as a biocontrol agent by depriving phytopathogens of iron nutrition [55]. Chincholkar et al., [56] studied an iron-binding pigment produced

by Pseudomonas fluorescence NCIM 5096 and found its utilization not only in plant growth promotion but in disease control. Some siderophore producing microorganisms are shown in **Fig 2**. There are some bacteria which produce one or more than one siderophore which can be utilized by other microorganisms for iron and other metal acquisition [54]. As compared to microbial siderophores, the affinity of phytosiderophores is less. Till now, 500 types of siderophores are reported from selected microorganisms [57], and significant variations are observed in the structure of siderophores from different species [54].



a. Control **b. Pseudomonas aeruginosa** **c. Trichoderma harzianum**

Fig 2. Siderophore produced by microbial cultures (a) control (b) Pseudomonas aeruginosa (c) Trichoderma harzianum on CAS agar plate

BIOLOGY AND CHEMISTRY OF SIDEROPHORES

Hydroxamate, catecholate and carboxylate are three different kinds of siderophores[52]. Hydroxamate which is found in both plants and fungi provides two oxygen molecules and forms a bidentate ligand with iron due to which each siderophore forms a hexadentate octahedral complex with ferric ion. Ferribactin produced by Pseudomonas is a hydroxamate siderophore, and gonobactin produced by Neisseria gonorrhoeaeis also a hydroxamate siderophore [58]. Ferrichrome a hydroxamate siderophore have a special ecological interest because it is produced by many soil fungi [59] (Table 1). Certain ferrichrome derivatives show antibiotic activity and are called ferrimycine [60]. Catecholates that are produced only by bacteria provide two oxygen atoms for chelation with Fe which forms a hexadentate octahedral complex same as in the hydroxamate siderophore .Enterobactin was the first tricatecholate type of siderophore isolated from E.coli. Enterobactin is the strongest siderophore, these siderophores chelates iron present in very low iron concentration in the environment [58]. Carboxylate siderophore is also produced by both fungi as well as bacteria, it is a novel class of siderophore. The member of this class neither possess hydroxamate nor phenolate ligands, iron binds with hydroxyl carboxylate and carboxylate groups [51].Ferrichrome, produced by the fungus *Ustilago sphaerogena*, was the first siderophore to be isolatedand has shown to be a growth factor for other microbes [51]. Fungi and bacteria both produce rhizoferin, but fungi produce only R- rhizoferin.Bacteria produce S-rhizoferin both are enantiomers [61]. Apart from these siderophores, some siderophores have mixed ligand, like pyoverdines/ pseudobactins which contains di-hydroxyl quinoline derivative (Table 6a). The chromophore di-hydroxyquinolineis linked to a peptide chain having two hydroxamate groups or one hydroxamate or one hydro-carboxylate group [51].Different types of fluorescent chromopeptides, termed pseudobactin or pyoverdines, are synthesized by Pseudomonas sp. [62].

Table 1. Types of bacterial and fungal siderophores

Type of Siderophore	Chemical Moiety	Functions	Bacterial Source	References
Catecholate: phenolate or 2,3- dihydroxy benzoate binding groups				
(a) Enterobactin	2,3- dihydroxy-N-benzoylserine a cyclic trimer	Iron-chelating compounds and used in agriculture	Family Enterobacteriaceae, e.g. E. coli	Gregory et al. 2012; Pollack &Neilands 1970; Walsh et al.,(1990)
Hydroxamate: esters or acid chlorides or carboxylic acids				
(a) Aferrioxamines	Linear trihydroxamates	Used medically for binding the excess iron in the blood in the treatment of thalassaemia	Streptomyces and Nocardia	IUPAC, commission on nomenclature of organic chemistry, 1993; O'Brien et al. 1970; Gregory et al. 2012
(b) Ferrichrome	Cyclic trihydroxamate	Growth factors for other microbes	Basidiomycetes producing fungal species, e.g. Ustilagos-phaerogena	Jalal & van der Helm 1991; O'Brien et al. 1970; IUPAC, Commission on the nomenclature of organic chemistry,1993; Gregory et al. 2012
(c) Aerobactin	A trihydroxytetraoxo tetra azatricosane-tricarboxylic acid	Sequester iron in iron-poor environments such as the urinary tract	Pseudomonas of marine origin, Klebisella pneumonia, Aerobacteraerogenes	Buyer et al. 1991; Meyrier 1999;
Carboxylate: hydroxyl carboxylate and carboxylates				
(a) Rhizoferrin	Diaminopropaneacylated with citric acid via amine bonds to the terminal carboxylate of citric acid	Biotechnological application: metal binding properties and ability to be easily degraded by various microorganisms	Fungi, specifically zygomycetes members	Winkelmann 1991; Stephan et al. 1996; IUPAC, Commission on the nomenclature of organic chemistry,1993;
Siderophore with mixed ligand				
(a) Lysine derivative (Myobactin)	Two structural classes based on the presence or absence of a 2-hydroxyphenyloxazolinering system	Chemotaxonomic markers for identification of mycobacteria upto species level	*M.tuberculosis, M. smergmatis*	Stephan et al. 1998; De Voss et al. 1999; Varma&Podila 2005
(b) Ornithine Derivative (Pyoverdine)	Chromophore, (1S)-5-amino-2,3-dihydro-8,9-dihydroxy-1H-pyrimido(1,2-a)quinoline -1-carboxylic acid	Prevention of iron overload toxicity inhibition of pathogenic bacterial growth	Pseudomonasaeruginosa	Wendenbaumet al. 1983; Lamont & Martin 2003; Meyer 2000

Siderophore-mediated iron transport

Microorganisms secrete iron trapping molecules i.e. siderophores under iron-deficient conditions into their external environment and form complexes with iron molecules (Fig3). After receiving this complex by cell surface receptors, many other transport complexes work in a sequence manner and finally released the siderophore iron complex into the cytoplasm. Mostly Gram-negative bacteria are reported, that produce iron scavenging molecules and transport the iron by using a siderophore. As microbes consist of various types of secretion systems including and all are ATP cassette transporters that transport molecules from the cell surface into the cytoplasm at the expense of ATP hydrolysis. Firstly, cell surface receptors bind these complexes with high fidelity as this binding is very specific and strong and transports this complex into the periplasm. During this transport, microbes change the structural confirmation into the receptor so that it can easily release the iron-siderophore complex inside the periplasm and for this various protein complexes are involved, e.g. Ton B. This complex converts one form of energy into another using proton motive force to bring the structural changes into the receptors for efficient transportation into the periplasm. After the complex reaches the periplasm, various siderophore-specific binding molecules are present including fhv A, fep B, and fec B, which bind to the siderophore and release iron into free form (Fig

3). Now, this free iron molecule is bounded by a periplasmic protein which translocates this iron into the cytoplasm by using cytoplasmic-associated transporters [51]. Pyoverdine (pvd) siderophores are produced by pseudomonads that are noticed to promote iron nutrition in different plant species (Arabidopsis, clover and grasses) [63].

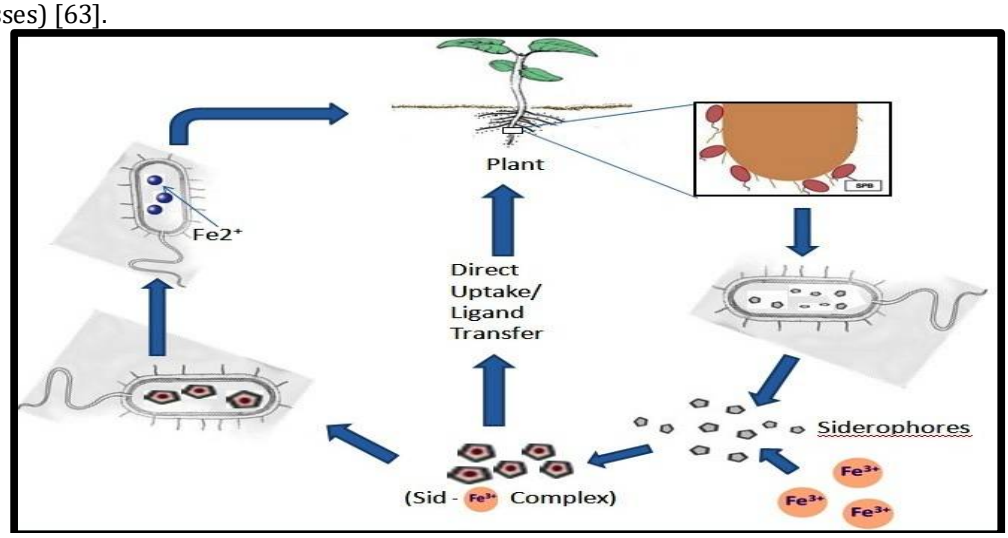


Fig 3 Mechanism of iron solubilization by siderophore produced by microorganisms.

Siderophore biosynthesis genes and its uptake regulations

Hohnadel and Mayer, [64] reported that there is an extensive homology present between the DNA of different species showing that the different siderophore synthesis genes evolved from the same ancestor. Various siderophore biosynthesis genes are illustrated in Table 2.

Table 2 Genes involved in siderophore biosynthesis

Genes	ORF	Functions
pvdA	PA2386	Ornithine hydroxylase
fpvR	PA2388	Anti-sigma factor for Pvds and Fpv1
fpvI	PA2387	ECF sigma factor required for the expression of fpvA
pvdF	PA2396	N5-Hydroxyornithine transformylase
pvdE	PA2397	ABC transporter (secretion)
fpvA	PA2398	Ferripyoverdine receptor protein
pvdD	PA2399	Pyoverdine peptide synthetase
pvdJ	PA2400/1	Pyoverdine peptide synthetase
pvdI	PA2402	Pyoverdine peptide synthetase
pvdS ECF iron sigma factor	PA2426	ECF iron sigma factor
pvcABCD	PA2254-PA2257	Synthesis of Pyoverdine chromophore

In Gram-negative bacteria, Fur (ferric uptake regulator) family including transcriptional repressors are responsible for the transcriptional regulation of these genes. Fur is a DNA-binding protein that requires a divalent heavy-metal ion as an activator. The gene product of the Fur gene also acts as a classical repressor and requires Fe^{2+}as an activator. When iron concentration is high, Fur forms a complex with Fe^{2+} in the promoter region which prevents transcriptions of these genes. In the case of iron-deficient conditions, Fe^{2+} is removed from Fur and fur-dependent genes are transcribed (Fig 4). Thus, Fur regulates iron metabolism [65]. Two other iron-regulated genes, fhuA and fepA, also reported which code for the ferrichrome and ferric enterobactin receptors, respectively. A palindromic "iron box,"5'-GATAATGATAATCATTATC-3", was suggested as the sequence recognized by the ferrous Fur complex [66]. Although Fur is an essential gene family for iron–controlled gene regulation, its mutation can have led to adverse effects. The P. aeruginosa fur gene transcription is regulated by tandemly arranged promoters. Out of all one promoter lies in the adversely oriented omlA gene. The downstream promoter hasa consensus sequence for RpoD-dependent RNA polymerase (RNAP), the upstream promoter does not contain any specific sequence, but there is a possibility of the requirement of additional regulatory proteins for transcription arising from this promoter [67].

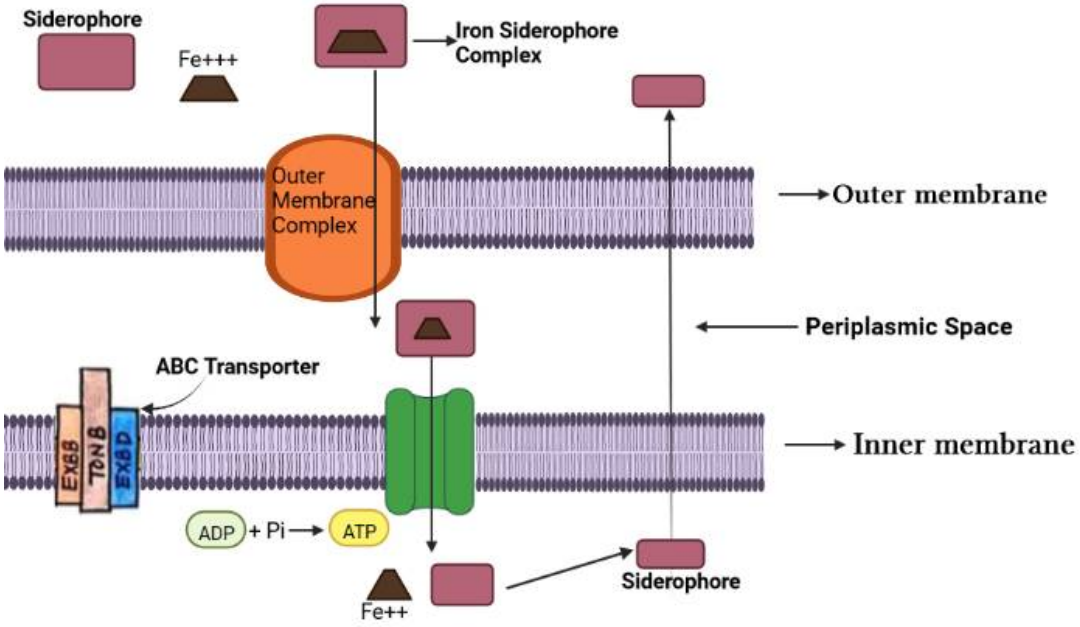


Fig 4Transport of iron across the outer and inner membrane.

Another class of siderophores biosynthetic gene family is Pyoverdines (pseudobactin in soil pseudomonads), which are chromophores having the fluorescent ability and are produced by the rRNA homology group l pseudomonads and some newly reported species. Like, most siderophores composed of three domains, Pyoverdines are likely to have the same, out of which peptidic domain specifically aids great strain-dependent diversity that reflects in the regulation of uptake specificity. It contains both usual and unusual amino acids, the latter include acylated or cyclic forms of N8-hydroxyornithine, diaminobutyrate, l3-hydroxyaspartate, l3-hydroxyhistidine, and D-amino acids [68]. All pyoverdines have a high affinity (Kf = 1032 M^{-1}) towards binding with Fe(III) that results in the formation of a hexadentate complex which includes the hydroxyl residues of the chromophore along with hydroxamate, hydroxyl, and carbonyl group of the peptidic moiety. The biosynthesis of pyoverdines is a complex process. The biosynthesis of the peptide moiety and the chromophore of pyoverdines are preceded by non-ribosomal peptide synthases activity [69]. These modular enzymes are large and regulate the multi-step reaction according to the carrier thiotemplate mechanism that results in outer membrane-bound proteins acting as receptors for the ferric diversity of pyoverdines. Moreover, a variety of enzymes are involved in pyoverdines biosynthesis and regulation. Also, another gene FpvA (ferric pyoverdine) encodes an iron-regulated pyoverdine, ferric pyoverdine116. CD spectroscopy analysis reported that FpvA is composed of 57% β structure, 3% α helix structure, and 40% random coils showing similarity with porins and other receptors of siderophore [70]. The ferric pyoverdine transport through the receptor FpvA is an active process i.e. energy-dependent process which proceeds with the help of three TonB homologues gene (tonB 1, tonB 2 and PA0695) that are identified in the genome of P. aeruginosa. The tonB1 is one of the important genes for the siderophore-mediated uptake of iron. This gene is Fur repressible and regulated by iron. Fur is repressible, and essential for siderophore-mediated iron uptake. The N terminal extension of FpvA shows a vital role in the activity of TonB1 and also prevents its degradation. Some reports also suggested that N terminal extensions are generally involved in signalling and the rest of the protein involved in pyoverdine transport. Indeed, a truncated FpvA fails to restore pyoverdine biosynthesis but can transport siderophores [71].

Binding of ferri-pyoverdines to FpvA generates a signalling pathway comprising cytoplasmic membrane spanning anti-sigma factor FpvR, ECF sigma factor PvdS shown in Fig 5. Interaction of FpvA with the periplasmic domain of FpvR results in the transduction of signal through the cytoplasmic membrane to the cytoplasmic domain of FpvR. FpvR generally regulates the ECE sigma factor PvdS activity [72].

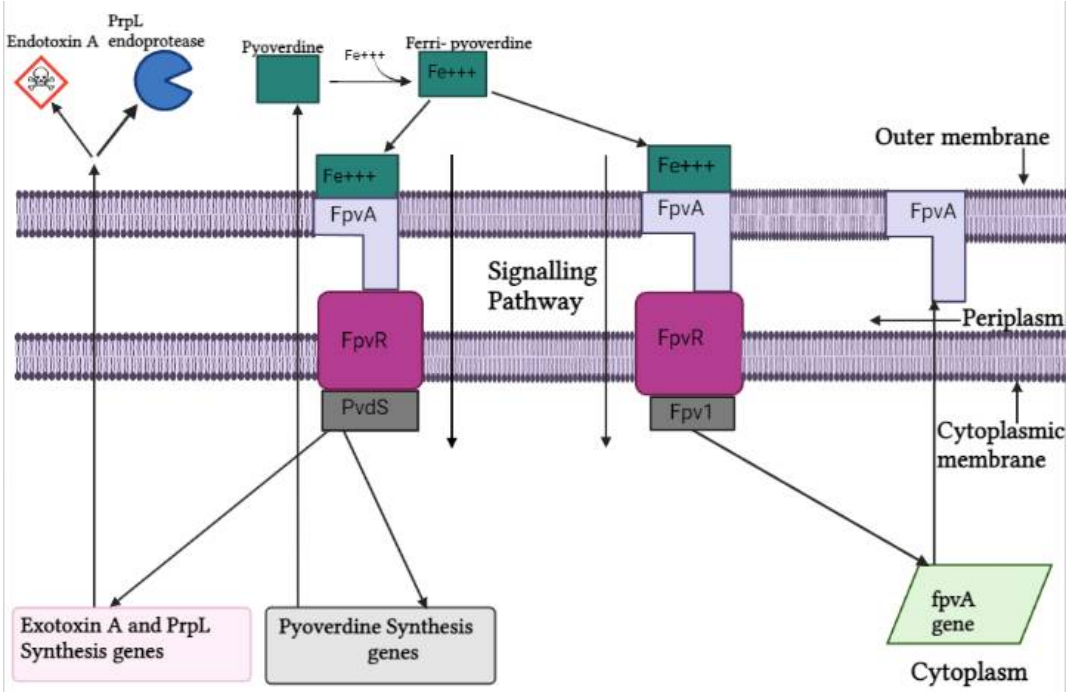


Fig 5 Schematic representation of Fpv signalling system.

Signal transmission results in the release of FpvI and PvdS from inhibition by FpvR. Some reports suggested that a helix-turn-helix (HTH) DNA binding motif is present in the FpvI sequence. FpvR gene is located adjacent to the FpvI orPvdS and it regulates the activity of both the genes. PvdS then bind to the RNA polymerase and initiate transcription of the genes that direct the expression of pyoverdines, secreted proteins exotoxin A and Prp Lendo protease; whereas FpvI initiates the expression of FpvA. The intergenic sequence between fpvI and fpvR contains overlapping divergent sigma 70(s 70) recognition sites (-35 and-10) for both fpvI and fpvR that were highly similar to those of the s 70 consensus sequence.The binding site of iron-responsive Fur repressor protein is located in the DNA of the intergenic region between FpvI and FpvR [73]. The intergenic region contains two Fur repressor recognition sites that overlap the S70–dependent promoters. Analysis of some data it is reported that the expression of FpvI and FpvR is regulated by the Fur family. The presence of iron in the growth medium results in the decreased production of FpvI and this is likely to repress the expression of fpvA. After these regulatory signals, pyoverdines are exported into the extracellular medium via a twin arginine translocation (TAT)-dependent mechanism. After excretion into the medium, the iron-pyoverdine complex is disrupted and it delivers iron to the cells following the receptor-mediated uptake mechanism. After that pyoverdines are recycled back and thus, proceed through several rounds of iron transport by the same molecule [71].

Applications of siderophores

Siderophores are the biological molecules produced by different types of microorganisms having a wide range of applications in various fields like agriculture, environmental applications, biocontrol, bioremediation and medicinal application [74]. In agriculture, inoculation of soil with Pseudomonas sp. produces pseudobactin which increases the growth of many plants [75]. It works as a biosensor as it can detect the content of iron in different environments [76]. Excessive accumulation of heavy metals in the soil becomes toxic to various plants; in this concern, hydroxamate siderophore present in soil plays an important role to immobilize metals [77]. Under metal stress, soil microorganisms including plant growth promoting bacteria (PGPB) have developed several strategies to evade the toxicity generated by the various heavy metals plant growth promoting bacteria (PGPB) have developed various strategies. Such metal-resistant PGPB, when utilized as bioinoculant or biofertilizers, significantly increased the growth of plants in heavy metal contaminated/stressed soils [78]. Research has concentrated on microbial-mediated redox transformations, that can change the redox chemistry of actinides through direct and indirect mechanisms, that affect their environmental solubility as well as mobility [78]. Siderophores themselves also act as growth inhibitors for many pathogenic fungi such as Pythium ultimum, and Fusarium oxysporum [79]. Kloepper et al. [75] were the first to report the importance of siderophore in controlling Erwinia carotovora. In the medical field, certain diseases like hemochromatosis, hemosiderosis and accidental iron

poisoning require iron removal from the body, mainly the liver. Such diseases can be treated with siderophore-based drugs.

CONCLUSION

Under aerated conditions in saline /alkaline soil, iron is found in extremely insoluble and fixed form, so its concentration becomes limited for optimal plant growth. Currently, several applications of siderophores are reported in various fields such as medicine, agriculture, biocontrol of phytopathogens, and environmental applications. It can also be applied for combating both biotic and abiotic stresses. It also has the potential for the treatment of diseases caused by pathogenic microorganisms by exploiting their antimicrobial property. There is a close relationship between siderophore utilization and virulence. The strategy of iron-dependent pathogen control is a promising field for future investigations and offers a wide array of possible therapeutic applications. However, research in the microbiological aspects of siderophore is still very limited. Combining metagenomics with detailed chemical analysis will disclose important information that could be used to improve its current applications and develop new applications for siderophores.

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REFERENCES

1. Kumari, Anita, et al. "Effects of short and long term salinity stress on physiological and oxidative metabolism in chickpea (Cicerarietinum) and its possible alleviation by nitric oxide." Indian J Ecol 44.2 (2017): 250-258.
2. AGRIFACTS (2003) Soil pH and plant nutrition. Practical Information for Albeta's Agriculture Industry. Accessonlineat: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/ all/agdex3896.
3. Sharma, T., Kumar, N., and Rai, N. (2012). Isolation, screening and characterization of PGPRisolates from rhizosphere of rice plants in Kashipur region (Tarai region). Journal ofBiotechnology International, 5(3): 69-84.
4. Vessey, J. K. (2003). Plant growth promoting rhizobacteria as biofertilizers. Plant and soil, 255(2), 571-586.
5. Liu, X., Fu, J. W., Tang, N., da Silva, E. B., Cao, Y., Turner, B. L. and Ma, L. Q. (2017). Phytateinduced arsenic uptake and plant growth in arsenic-hyper accumulator Pterisvittata. Environmental Pollution, 226: 212-218.
6. Kumar, P., & Sharma, P.K. (2020).Soil Salinity and Food Security in India. Frontiers in Sustainable Food Systems.
7. Ali, S S., and Vidhale, N N. (2013). Bacterial Siderophore and their Application: A review,.Int.J.Curr.Microbiol.App.Sci, 2(12): 303-312.
8. Ujjal, M. "challenges and side effects of heavy metals in agriculturechallenges and side effects of heavy metals in agriculture." International Journal of Modern Agriculture 10.2 (2021): 1198-1205.
9. Musyimi, D. M., Netondo, G. W., &Ouma, G. (2007).Effects of salinity on gas exchange and nutrients uptake in avocados. Journal of Biological Sciences, 7(3), 496-505.
10. Aycan, Murat, et al. "Development of new high-salt tolerant bread wheat (Triticumaestivum L.) genotypes and insight into the tolerance mechanisms." Plant Physiology and Biochemistry 166 (2021): 314-327.
11. Chen, G. Y., & Ayres, J. S. (2020). Beyond tug-of-war: iron metabolism in cooperative host–microbe interactions. PLoS Pathogens, 16(8), e1008698.
12. Warrence, N., Bauder, J. W., & Pearson, K. E. (2003).Basics of salinity and sodicity effects on soil physical properties.Adapted by Krista E.
13. Schmidt, W., Thomine, S., &Buckhout, T. J. (2020).Editorial: Iron Nutrition and Interactions in Plants. Frontiers in plant science, 10, 1670. https://doi.org/10.3389/fpls.2019.01670
14. Chhibber, S., Nag, D., and Bansal, S. (2013). Inhibiting biofilm formation by Klebisellapneumonia B5055 using an iron antagonizing molecule and a bacteriophage. BMCMicrobiology, 13(1): 174.
15. Li, J., Cao, X., Jia, X., Liu, L., Cao, H., Qin, W., & Li, M. (2021). Iron Deficiency Leads to Chlorosis Through Impacting Chlorophyll Synthesis and Nitrogen Metabolism in Areca catechu L. Frontiers in plant science, 12, 710093. https://doi.org/10.3389/fpls.2021.710093
16. Joshi, F., Chaudhari, A., Joglekar, P., Archana, G., and Desai, A. (2008).Effect of expressionof Bradyrhizobiumjaponicum 61A152 fegA gene in Mesorhizobium sp., on it competitive survival and nodule occupancy on Arachis hypogea.Applied SoilEcology, 40(2): 338-347.
17. Schulte, E.E. (2004). Soil and applied iron. Understanding Plant Nutrients, A3554
18. Liu, X., Fu, J. W., Tang, N., da Silva, E. B., Cao, Y., Turner, B. L. and Ma, L. Q. (2017). Phytateinduced arsenic uptake and plant growth in arsenic-hyper accumulator Pterisvittata. Environmental Pollution, 226: 212-218.

19. Connorton, J. M., Balk, J., & Rodríguez-Celma, J. (2017). Iron homeostasis in plants - a brief overview. Metallomics : integrated biometal science, 9(7), 813–823. https://doi.org/10.1039/c7mt00136c
20. Hartmond U, Schaesberg NV, Graham JH, Syverten JP (1987)Salinity and flooding stress effects on mycorrhizal and non-mycorrhizal citrus rootstock seedlings. Plant Soil 104:37–43
21. Adhikari, T. (2015).Phytometallophore-Mediated nutrient acquisition by plants. In Nutrient Use Efficiency: from Basics to Advances (pp. 401-414). Springer, New Delhi.
22. Shaygan, M., &Baumgartl, T. (2022).Reclamation of Salt-Affected Land: A Review. Soil Systems, 6(3), 61.
23. Figueroa, L., Schwarz, B., & Richards, A. M. (2015). Structural characterization of amphiphilic siderophores produced by a soda lake isolate, Halomonas sp. SL01, reveals cysteine-, phenylalanine-and proline-containing head groups. Extremophiles, 19(6), 1183-1192.
24. Bhattacharyya, P. N., &Jha, D. K. (2012).Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. World Journal of Microbiology and Biotechnology, 28(4), 1327-1350.
25. Whipps, J. M. (2001). Microbial interactions and biocontrol in the rhizosphere. Journal of experimental Botany, 52(suppl_1), 487-511.
26. dos Santos, R. M., Diaz, P. A. E., Lobo, L. L. B., &Rigobelo, E. C. (2020). Use of plant growth-promoting rhizobacteria in maize and sugarcane: Characteristics and applications. Frontiers in Sustainable Food Systems, 4, 136.
27. Sagar, A., Rathore, P., Ramteke, P. W., Ramakrishna, W., Reddy, M. S., &Pecoraro, L. (2021).Plant growth promoting rhizobacteria, arbuscularmycorrhizal fungi and their synergistic interactions to counteract the negative effects of saline soil on agriculture: Key macromolecules and mechanisms. Microorganisms, 9(7), 1491.
28. Afzal, I., Shinwari, Z. K., Sikandar, S., &Shahzad, S. (2019). Plant beneficial endophytic bacteria: Mechanisms, diversity, host range and genetic determinants. Microbiological research, 221, 36-49.
29. Jiang, H., Li, S., Wang, T., Chi, X., Qi, P., & Chen, G. (2021). Interaction Between Halotolerant Phosphate-Solubilizing Bacteria (Providenciarettgeri Strain TPM23) and Rock Phosphate Improves Soil Biochemical Properties and Peanut Growth in Saline Soil. Frontiers in microbiology, 12, 777351.https://doi.org/10.3389/fmicb.2021.777351
30. Han, H. S., and Lee, K. D. (2005). Plant growth promoting rhizobacteria effect on antioxidantstatus, photosynthesis, mineral uptake and growth of lettuce under soil salinity.Res J AgricBiolSci, 1(3): 210-215.
31. Zhao, Y., Selvaraj, J. N., Xing, F., Zhou, L., Wang, Y., Song, H., .and Liu, Y. (2014).Antagonistic action of Bacillus subtilis strain SG6 on Fusarium graminearum. PloS One, 9(3)1: e92486
32. Poosapati, S., Ravulapalli, P. D., Tippirishetty, N., Vishwanathaswamy, D. K., and Chunduri,S. (2014). Selection of high temperature and salinity tolerant Trichoderma isolateswith antagonistic activity against Sclerotiumrolfsii. SpringerPlus, 3(1): 641.
33. Egamberdieva, D., Wirth, S., Bellingrath-Kimura, S. D., Mishra, J., &Arora, N. K. (2019).Salt-tolerant plant growth promoting rhizobacteria for enhancing crop productivity of saline soils. Frontiers in microbiology, 10, 2791.
34. Barooah, M., Goswami, G., & Bora, S. S. (2021). Plant Growth-Promoting Rhizobacteria (PGPR): A New Perspective in Abiotic Stress Management of Crop Plants.In Microbial Metatranscriptomics Belowground (pp. 655-679).Springer, Singapore.
35. Radzki, W., Gutierrez Mañero, F. J., Algar, E., Lucas García, J. A., García-Villaraco, A., & Ramos Solano, B. (2013). Bacterial siderophores efficiently provide iron to iron-starved tomato plants in hydroponics culture. Antonie van Leeuwenhoek, 104(3), 321–330. https://doi.org/10.1007/s10482-013-9954-9
36. Albelda-Berenguer, M., Monachon, M., & Joseph, E. (2019).Siderophores: From natural roles to potential applications. Advances in applied microbiology, 106, 193-225.
37. Ahmed, E., &Holmström, S. J. (2014).Siderophores in environmental research: roles and applications. Microbial biotechnology, 7(3), 196-208.
38. Takase, H., Nitanai, H., Hoshino, K., &Otani, T. (2000).Impact of siderophore production on Pseudomonas aeruginosa infections in immunosuppressed mice. Infection and immunity, 68(4), 1834-1839.
39. Yu, X., Ai, C., Xin, L., & Zhou, G. (2011). The siderophore-producing bacterium, Bacillus subtilis CAS15, has a biocontrol effect on Fusarium wilt and promotes the growth of pepper. European Journal of Soil Biology, 47(2), 138-145.
40. Baars, O., Zhang, X., Morel, F. M., &Seyedsayamdost, M. R. (2016).The siderophore metabolome of Azotobacter vinelandii. Applied and environmental microbiology, 82(1), 27-39.
41. Singh, S. K., Verma, H., Singh, V. K., Ghosh, S., Giri, D. D., Mishra, M., & Kumar, A. (2021).Sustainable agricultural practices using microbial strains for crop production. In Food Security and Plant Disease Management (pp. 357-370). Woodhead Publishing.
42. Rawat, R., and Tewari, L. (2011). Effect of abiotic stress on phosphate solubilization bybiocontrol fungus Trichoderma sp. Current Microbiology, 62(5): 1521-1526.
43. Prabhavati, E., and Mallaiah, K. V. (2008).Effect of salt concentration on siderophoreproduction by Rhizobium strains nodulatingMacrotylomauniflorum (Lam.) verdc.Asian Journal of Bio Science, 3(2): 352-354.
44. Deshwal, V. K., and Kumar, P. (2013).Effect of salinity on growth and PGPR activity ofPseudomonads. Journal of Academia and Industrial Research, 2(6): 353-356.
45. Tank, N., and Saraf, M. (2009). Enhancement of plant growth and decontamination of nickelspiked soil using PGPR. Journal of Basic Microbiology, 49(2): 195-204.
46. Singh, A., and Mishra, A. K. (2015). Influence of various levels of iron and other abioticfactors on siderophorogenesis in paddy field cyanobacterium Anabaena oryzae.Applied biochemistry and biotechnology, 176(2): 372-386.

47. Gascoyne, D. J., Connor, J. A., and Bull, A. T. (1991).Isolation of bacteria producingsiderophores under alkaline conditions. Applied Microbiology and Biotechnology,36(1): 130-135.
48. McMillan, D. G., Velasquez, I., Nunn, B. L., Goodlett, D. R., Hunter, K. A., Lamont, I., andCook, G. M. (2010). Acquisition of iron by alkaliphilic Bacillus species. Applied andEnvironmental Microbiology, 76(20): 6955-6961.
49. Figueroa, L., Schwarz, B., & Richards, A. M. (2015). Structural characterization of amphiphilic siderophores produced by a soda lake isolate, Halomonas sp. SL01, reveals cysteine-, phenylalanine-and proline-containing head groups. Extremophiles, 19(6), 1183-1192.
50. Ferreira, C., Vilas-Boas, Â., Sousa, C. A., Soares, H., &Soares, E. V. (2019). Comparison of five bacterial strains producing siderophores with ability to chelate iron under alkaline conditions. AMB Express, 9(1), 78. https://doi.org/10.1186/s13568-019-0796-3
51. Sah, S., and Singh, R. (2015).Siderophore: Structural and Functional Characterisation–AComprehensive Review. Agriculture (Polnohospodárstvo), 61(3): 97-114.
52. Tonziello, G., Caraffa, E., Pinchera, B., Granata, G., &Petrosillo, N. (2019).Present and future of siderophore-based therapeutic and diagnostic approaches in infectious diseases. Infectious disease reports, 11(2), 8208. https://doi.org/10.4081/idr.2019.8208
53. Lewin, R. (1984). How microorganisms transport iron. Science, 225(4660): 401-402
54. Ali, S S., and Vidhale, N N. (2013). Bacterial Siderophore and their Application: A review,.Int.J.Curr.Microbiol.App.Sci, 2(12): 303-312.
55. Pattan, J., Kajale, S., and Pattan, S. (2017). Isolation, Production and Optimization of Siderophores (Iron Chelators) from Pseudomonas fluorescence NCIM 5096 andPseudomonas from Soil Rhizosphere and Marine Water. Int. J. Curr. Microbiol. App.Sci, 6(3): 919-928.
56. Chincholkar, S. B., Chaudhari, B. L., &Rane, M. R. (2007).Microbial siderophore: a state of art. Microbial siderophores, 233-242.
57. Rapti, S., Boyatzis, S. C., Rivers, S., &Pournou, A. (2021). Siderophores and their Applications in Wood, Textile, and Paper Conservation.Microorganisms in the Deterioration and Preservation of Cultural Heritage, 301-339.
58. Khan, A., Singh, P., &Srivastava, A. (2018).Synthesis, nature and utility of universal iron chelator–Siderophore: A review.Microbiological research, 212, 103-111.
59. Aguiar, M., Orasch, T., Misslinger, M., Dietl, A. M., Gsaller, F., & Haas, H. (2021).The Siderophore Transporters Sit1 and Sit2 Are Essential for Utilization of Ferrichrome-, Ferrioxamine- and Coprogen-Type Siderophores in Aspergillus fumigatus. Journal of fungi (Basel, Switzerland), 7(9), 768. https://doi.org/10.3390/jof7090768
60. Braun, V., Pramanik, A., Gwinner, T., Köberle, M., & Bohn, E. (2009).Sideromycins: tools and antibiotics. Biometals : an international journal on the role of metal ions in biology, biochemistry, and medicine, 22(1), 3–13. https://doi.org/10.1007/s10534-008-9199-7
61. Pecoraro, L., Wang, X., Shah, D., Song, X., Kumar, V., Shakoor, A., Tripathi, K., Ramteke, P. W., & Rani, R. (2021).Biosynthesis Pathways, Transport Mechanisms and Biotechnological Applications of Fungal Siderophores. Journal of fungi (Basel, Switzerland), 8(1), 21. https://doi.org/10.3390/jof8010021
62. Trapet, P., Avoscan, L., Klinguer, A., Pateyron, S., Citerne, S., Chervin, C., ...&Besson-Bard, A. (2016). The Pseudomonas fluorescens siderophore pyoverdine weakens Arabidopsis thaliana defense in favor of growth in iron-deficient conditions. Plant physiology, 171(1), 675-693.
63. Lurthy, T., Cantat, C., Jeudy, C., Declerck, P., Gallardo, K., Barraud, C., Leroy, F., Ourry, A., Lemanceau, P., Salon, C., &Mazurier, S. (2020). Impact of Bacterial Siderophores on Iron Status and Ionome in Pea.Frontiers in plant science, 11, 730.https://doi.org/10.3389/fpls.2020.00730
64. Hohnadel D, Meyer JM (1988) Specificity of pyoverdine-mediated iron uptake among fluorescent Pseudomonas strains. J Bacteriol 170:4865–4873
65. Hantke, K. (2001). Iron and metal regulation in bacteria. Current Opinion in microbiology,4(2): 172-177.
66. BaGG, A., &Neilands, J. B. (1987).Molecular mechanism of regulation of siderophore-mediated iron assimilation.Microbiological reviews, 51(4), 509.
67. Ochsner, UA.,Vasil, A.I., Johnson, Z., and Vasil, M.L., 1999, Pseudomonas aeruginosaFuroverlaps with a gene encoding a novel outer membrane lipoprotein, OmlA. J. Bacteriol., 181:1099-1109.
68. Meyer, J.M., 2000, Pyoverdines: Pigments, siderophores and potential taxonomic markers of fluorescent Pseudomonas species. Arch. Microbial., 174:135-142.
69. Crosa, J H. and Walsh, C.T., 2002, Genetics and assembly line enzymology of siderophore biosynthesis in bacteria. Microbiol.Mol. Biol. Rev., 66:223-249.
70. Schalk, I. J., Hannauer, M., and Braud, A. (2011).New roles for bacterial siderophores inmetal transport and tolerance. Environmental Microbiology, 13(11): 2844-2854.
71. Adams, H., Zeder-Lutz, G., Schalk, I., Pattus, F., & Celia, H. (2006).Interaction of TonB with the outer membrane receptor FpvA of Pseudomonas aeruginosa.Journal of bacteriology, 188(16), 5752–5761. https://doi.org /10.1128/JB.00435-06
72. Lamont, I.L., Beare, P.A., Ochsner, U., Vasil, A.I., and Vasil,M.L. (2002) Siderophore-mediated signaling regulates virulencefactor production in Pseudomonas aeruginosa. ProcNatlAcadSci USA 99: 7072–7077.
73. Ochsner, UA.,Vasil, A.I., Johnson, Z., and Vasil, M.L., 1999, Pseudomonas aeruginosaFuroverlaps with a gene encoding a novel outer membrane lipoprotein, OmlA. J. Bacteriol., 181:1099-1109.

74. Saha, M., Sarkar, S., Sarkar, B., Sharma, B. K., Bhattacharjee, S., &Tribedi, P. (2016). Microbial siderophores and their potential applications: a review. Environmental science and pollution research international, 23(5), 3984–3999. https://doi.org/10.1007/s11356-015-4294-0
75. Kloepper, J. W., Leong, J., Teintze, M., and Schroth, M. N. (1980). Enhanced plant growth by siderophores produced by plant growth-promoting rhizobacteria. Nature,286(5776): 885-886.
76. McGrath, S. P., Chaudri, A. M., and Giller, K. E. (1995). Long-term effects of metals inSewage sludge on soils, microorganisms and plants. Journal of IndustrialMicrobiology and Biotechnology, 14(2): 94-104
77. Ahemad, M. (2019).Remediation of metalliferous soils through the heavy metal resistant plant growth promoting bacteria: Paradigms and prospects. **Arabian Journal of Chemistry**.
78. Renshaw, J. C., Lloyd, J. R., & Livens, F. R. (2007). Microbial interactions with actinides and long-lived fission products.ComptesRendusChimie, 10(10-11), 1067-1077.
79. Wang, H., Liu, R., You, M. P., Barbetti, M. J., & Chen, Y. (2021).Pathogen Biocontrol Using Plant Growth-Promoting Bacteria (PGPR): Role of Bacterial Diversity. Microorganisms, 9(9), 1988.https://doi.org/10.3390/microorganisms9091988

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