

## Auxin originated from Actinobacteria participates in abiotic stress mitigation and sustainable crop production

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### Abstract

Plants activate their defence mechanisms to prevent damage caused by environmental stimuli through signaling pathways controlled by growth regulators. These stresses adversely affect plants' growth, disrupting the genetic control of cellular pathways and altering their metabolism, physiology and morphology. Auxin influences phenotypic plasticity under optimal and unfavourable growth conditions. This review discusses the progress in the research on auxin-mediated stress alleviation in response to abiotic stresses in plants. Then, a brief presentation of studies emphasizing the significance of auxin-producing actinobacteria and how microbial auxin promotes plant development and stress tolerance. Then, the review probes the importance of actinobacteria strains as auxin metabolic engineers and their use as natural auxin suppliers in agriculture. Finally, the review explores future biotechnology possibilities through small-scale, large-scale production and agriculture's gradual banishment of chemical phytosanitary inputs.

**Keywords:** abiotic stress management; Actinobacteria; auxin; plant growth promotion; sustainable agriculture

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### Introduction

Plant roots play a significant role in the phyto-nutrition and tolerance to diverse abiotic stresses that interfere with plant growth and pose significant threats to crop output (Alloun *et al.*, 2023). Nevertheless, several attempts are necessary to attain genetic stability for breeding new resistant varieties and delivering the desired result. Furthermore, despite the environment's resourceful abundance of essential macronutrients, they remain in an unassimilable form for roots, and their scarcity can threaten plant growth. The root system links between soil surroundings and shoots through signals transduction cascades. Thus, elaborate metabolic and

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signaling pathways mediate the abiotic stress-related physiological responses and the morphological alteration of roots (Zhang *et al.*, 2020).

Plants deploy two strategies to adapt to these challenging conditions: changing endogenous growth regulators' signalling pathways and selectively attracting a microbiome (Pascale *et al.*, 2020). According to this perspective, integrating cutting-edge eco-friendly management techniques is necessary for optimal plant growth (Soumare *et al.*, 2021).

The interactions between plants and their associated microbiomes result from the ability of plant growth-promoting rhizobacteria (PGPR), including actinobacteria, to nutrients cycling and biological control of fungal pathogens and phytohormones production such as auxins (Pereira *et al.*, 2016). Thus, constituting a safer, green alternative to fertilizers and pesticides (Alloun *et al.*, 2023). Indole-3-acetic acid (IAA) is an essential natural phytohormone and a representative member of the auxin family, controlling various vital physiological and developmental processes in plants. Plants and microbes produce auxin via several interconnected pathways, including the tryptophan-dependent pathway (Duca and Glick, 2020). The evidence that Actinobacteria have been discovered to produce physiologically active IAA that might be used for commercial auxin production is significant (Alloun *et al.*, 2023; Boubekri *et al.*, 2021). The multifunctionality of Actinobacteria is highlighted by its bioactivity potential in terms of disease suppression (Toumatia *et al.*, 2016) and plant growth stimulation (Borah and Thakur, 2020). However, most of these strains still need to be explored in agriculture.

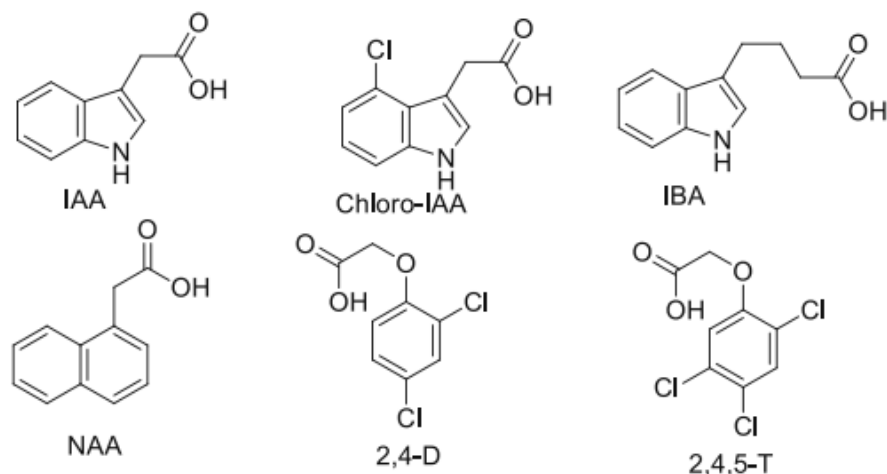
This review highlights recent progress in the mechanisms underlying the growth promotion activities of actinobacterial species within the plant microbiome, their potential use in modern sustainable agricultural systems, the role of auxin in plant physiology, and the root phenotypic plasticity and responses to favourable and adverse growth conditions. The review will next describe recent advancements in cost-effective large-scale IAA synthesis, biotechnological use of actinobacterial metabolic engineering as phytosanitary products (bio inoculants, phyto-stimulants, and biocontrol agents) to replace synthetic phytohormones and agrochemical substances to move to more sustainable management practices.

### **Auxin mediated root morphology modulation**

IAA, an essential endogenous phytohormone, has been discovered to coordinate almost all physiological and morphological aspects of plant growth and development during its stages (Robert *et al.*, 2018). IAA controls several distinct characteristics in plants, including cell-cell signalling, plant organs' response—primarily roots and shoots—to environmental cues, and the development of plant defence mechanisms. However, there is a lack of knowledge regarding auxin sensing and signaling, which accounts for the actual auxin-induced responses during plant growth (Zhang *et al.*, 2020). Figure 1 depicts the chemical compositions of the auxin family's natural and synthetic members consisting of the 2,4-dichlorophenoxyacetic acid (2,4-D), the 2,4,5-trichlorophenoxyacetic acid (2,4,5-T), indole butyric acid (IBA) and the 1-naphthaleneacetic acid (NAA).

Similarly, according to Patten *et al.* (2013), IAA modulates specific tropic responses to light and gravity known as phototropism, shade avoidance, and gravitropism, respectively. Moreover, IAA have an impact on photosynthesis and the synthesis of plant metabolites. auxin also controls the initiation of lateral and adventitious roots, apical dominance, the activation of cell division, and the stimulation of stem and root extension (Duca and Glick, 2020).

IAA is a chemical signaling controlling vital physiological processes in plants starting from the function throughout plant growth, establishment, and adaptation of root system architecture (RSA). IAA is a crucial hormone for the active control and modulation of root developmental plasticity. Therefore, modulation of Phenotypic Plasticity (PP), which comprises all required RSA developmental adjustments, is essential for the plant's capacity to tolerate diverse stresses.



**Figure 1.** The chemical structures of natural and synthetic auxins derived from indole acetic acid. 2,4-dichlorophenoxyacetic acid (2,4-D) and 2,4,5-trichlorophenoxyacetic acid (2,4,5-T), indole butyric acid (IBA), 1-naphthaleneacetic acid (NAA)

IAA, for example, initiates root emergence and accelerates its growth by modifying root length, which is followed by an increase in the number of root branches, root hairs, and root laterals that assist in the plant's ability to absorb nutrients from the environment (Zhang *et al.*, 2020).

Contrary to other phytohormones, auxin-induced morphogenesis and adaptabilities to various environmental cues are concentration-dependent processes. These responses require asymmetrical auxin dispersion among plant cells, with the effective range varying depending on the plant species and rooting stage (Duca and Glick, 2020). As a result, auxin gradients, which are influenced by auxin transport, govern the PP of the roots and other auxin-controlled processes in plants. However, higher amounts of auxin are suggested to suppress root elongation by raising the levels of ethylene that hinder plant growth.

### Crosstalk between auxin and phytohormones under combined stress

Regarding the complexity of endogenous auxin homeostasis and regulation as a response to external stimuli during the exposure of the plant to various stresses, new hypotheses can be developed based on the abounding empirical evidence in the literature on the interactive chemical network between auxin and other phytohormones (Alloun *et al.*, 2023). It has been proposed that the cooperative action of various combinations of phytohormones, including *Crosstalk*, is necessary to produce the fundamental changes in root PP and, as a result, to regulate physiological processes associated with plant growth under stressful conditions.

According to research by Camacho-Cristóbal *et al.* (2015), auxin, ethylene, and reactive oxygen species (ROS) cooperate to inhibit cell elongation in *Arabidopsis* plants during boron (B) deprivation as a result of alterations in auxin distribution. For example, it has been proposed that heavy metals increase the accumulation of ethylene, which may combine with auxin to form a signaling circuit to support the plant's ability to withstand stress, and that this pathway may be the reason for the changes in root architecture (Li *et al.*, 2015). The genes coding for auxin biosynthesis are activated by ethylene, increasing the amount generated. As a plant response to this stressor, the PIN-FORMED proteins (PIN1), which constitute secondary auxin efflux carriers is downregulated. Ethylene also alters the delivery of auxin to the elongation zone. Additionally, copper (Cu)-induced nitric oxide (NO) accumulation is a regulator of auxin transport, resulting in a reduction in its endogenous pool at the root apex and a considerable reduction in root meristem growth, which confirms that

NO and Auxin are involved in the inhibition of *Arabidopsis* root meristem growth by auxin signal transduction during plant exposure to Cu stress (Yuan and Huang, 2016).

### **Auxin and abiotic stress alleviation in plants**

During oxidative stress, auxin controls ROS levels. However, ascorbate peroxidase 6 coordinates the crosstalk between ROS, auxin, and abscisic acid (ABA) and promotes tolerance to drought stress (Jogawat *et al.*, 2021). Auxin and ABA also cooperate to stimulate root development. On the other hand, auxin signaling is pointed by many microRNAs in response to abiotic stress, including miR393 and miR160 (ARF4) for drought stress (Bashir *et al.*, 2019).

Nonetheless, other abiotic stimuli, such as metalloids, disrupted the expression of miRNA164, miRNA167, and miRNA390, which are involved in auxin control (Singh *et al.*, 2021). However, the effects of metalloids are not fixed attributes. For instance, selenium (Se) and arsenic (As) restricted auxin and ethylene production, impacting root development and primary metabolism. Moreover, B generates advanced aluminium (Al) accumulation while reducing its toxicity (Singh *et al.*, 2021) by boosting root surface alkalization, which auxin controls, and regulating the proton pump H<sup>+</sup>-ATPase, therefore improving Al assimilation. Furthermore, silicon (Si) raises IAA levels and zinc (Zn) levels necessary for IAA synthesis, figuring out the role of Si in heavy metal stress resistance (Singh *et al.*, 2021). Overexpression of the tryptophan-2-monooxygenase during abiotic stress increases auxin levels, improving drought tolerance (Bielach *et al.*, 2017).

Drought stress also induces overexpression of DREB2A/B, which enhances transcription of three AUX/IAA suppressor proteins involved in stomatal closure regulation while decreasing the expression of WRKY63, which controls GLs aliphatic production (Salehin *et al.*, 2019).

AUX/IAA influx symporters involved in auxin transport compete with phosphatidic acid to ensure plant halotropism. Auxin also has a role in regulating flavonoid amounts. In exchange, flavonoids inhibit auxin degradation and bind to Glutathione 5-transferase phi-2 transcripts to control auxin trafficking during the stress response, like salt stress (Salem *et al.*, 2020). Auxin production increased in response to shade stress, and YUC2, YUC5, YUC8, and YUC9 levels increased during shade treatment before returning to baseline after 96 hours. Moreover, various abiotic stressors trigger YUC6 gene responses that are endowed with thiol-reductase activity, which reduces ROS activity and hence preserves IAA (Mroue *et al.*, 2018).

The increase of auxin as an abiotic stress response was mainly linked to a decrease in ROS, knowing that the drought resistance was associated with an auxin-dependent drop in H<sub>2</sub>O<sub>2</sub> and O<sub>2</sub> levels (Bielach *et al.*, 2017). Cytokinin oxidase AtCKX6 gene is overexpressed when plants are exposed to shade stress, which increases auxin production that modulates cytokinin levels (Mroue *et al.*, 2018). Moreover, IAA peroxidases regulate IAA levels during root growth and hypocotyl elongation (Bielach *et al.*, 2017).

Previous studies demonstrated that exogenous administration of IAA can simulate drought resistance, decrease ROS generation, stimulate stress-related genes, and induce the antioxidant mechanism. On the other hand, lower amounts of auxin result in higher ROS accumulation and reduced drought tolerance in *yuc1 yuc2 yuc6* triple mutants (Bielach *et al.*, 2017).

### **Auxin-phytohormones interaction influences plant's secondary metabolism**

Different physiological processes, like differentiation, development, and growth, may be regulated by a single plant hormone. However, auxin-cytokinin interaction is necessary to regulate the regular physiological processes in plant tissue and organ cultures. However, many phytohormones acting simultaneously at low concentrations control metabolic processes and gene regulation. Interestingly, changes to the auxin, cytokinin, or auxin/cytokinin ratio pools, as well as secondary metabolism in plants, may all have a significant impact. The

auxin/cytokinin ratio regulates growth and shape. Additionally, depending on the plant species, plant growth regulators negatively impact the generation of secondary metabolites *in vitro* culture systems.

For instance, according to Parić *et al.* (2017), the 6-Benzylaminopurine (BAP) and indole butyric acid (IBA) could promote the formation of total phenolics and flavonoids. While the addition of BAP and IBA did not significantly alter the synthesis of plant secondary compounds, BAP alone boosted the total yield of essential oils and its components (menthone, menthol, pulegone, and menthofuran) in *M. piperita* (Parić *et al.*, 2017).

Natural auxins (IBA and IAA), as well as synthetic auxins (2,4-D and NAA), stimulated the synthesis of anthocyanins in hairy root cultures of the Tartary buckwheat cultivar Hokkai T10 (Park *et al.*, 2016). In roselle plants, combining IAA and gibberellic acid (GA3) may increase flavonoids, b-carotene, and chlorophyll (Mirheidari *et al.*, 2021).

### **Current research in large-scale microbial auxin production using low-cost substrates and commercialization**

#### *Phytohormones market*

According to a recent assessment of global trends in phytohormone research, auxin's discovery was relevant to 53 nations. It typically conveys the nation's attention to the current and upcoming economic demands. The population is growing faster than ever, which has increased the demand for food production increasing the need for high crop yields (Keswani *et al.*, 2020). The use of synthetic IAA has resulted in improved plant quality. It increased its revenues from US\$ 8.5 million in 2013 to US\$ 10.7 million in 2016 and then to US\$ 24 million in 2020, with an average annual growth rate of 7.97% over the preceding ten years. Over the next six years, the IAA market's revenue will grow at a 5.3% CAGR. As a result, the global market will grow to US\$ 34 million by 2027. However, chemical synthesis has several problems, including complex operation and low purity. Demand is also restricted because of the synthetic substance's high level of toxicity and the possibility that improper use could result in skin, eye, and respiratory irritation (Keswani *et al.*, 2020). Thus, the production of IAA from microorganisms is recently gaining interest.

#### *Low-cost substrates for microbe-originated auxin production*

The environmentally benign technology that addresses the issues mentioned above and offers excellent long-term consistent benefits to farmers and consumers is the microbial synthesis of plant hormones (Bunsangiam *et al.*, 2021; Mushtaq, 2021). The final products obtained using this process have more promising bioactivity, purity, and lower costs while still being safe for farmers and the environment.

Organic products that could address the issue of environmental contamination today would ensure a satisfying level of profits in terms of food quality and quantity. Due to the market's scarcity of biofertilizers and biopesticides, there may be some economic problems. Numerous studies have focused on mutagenesis and efficiently screening bacteria and fungi that produce auxin (Alloun *et al.*, 2023).

In a 2-L capacity bioreactor with a submerged batch operating mode, Luziatelli *et al.* (2021) proved the biotechnological potential of *Enterobacter* sp. in the production of auxin. Additionally, the benchtop fermenter's growing of this strain boosted the auxin yield by improving the culture conditions and medium composition. These modifications included changing the (i) culture medium's casein content to vegetable peptone and (ii) reducing fermentation duration from 72 to 24 hours by (iii) duplicating the inoculum size, which enhanced auxin output from 6.4 to 17.2 mg [IAAequ]/L/h.

These findings demonstrated the applicability and suitability of the suggested technique for an auxin/IAA production scale-up process. It demonstrated financial and environmental benefits that make the fermentative technique widely exploitable for creating plant-biostimulants suitable for organic and vegan farming. Thus, it is interesting to use a vegetable-peptone based growth medium (Luziatelli *et al.*, 2021).

The tryptophan-independent pathway also provides information about IAA biosynthesis. Its addition in growth media induced the production and accumulation of IAA. A sustainable alternative in the future could be the valorization of agricultural wastes high in tryptophan for the microbial synthesis of IAA (Alloun *et al.*, 2023). Oats wastes, such as straw or hulls, can substitute various pricey media that call for the addition of tryptophan, making their usage as a cost-effective fermentation medium for the synthesis of IAA practical and with the potential to lower expenses.

Using crude glycerol as a less expensive alternative substrate, Bunsangiam *et al.* (Bunsangiam *et al.*, 2021) recently presented the results of the first research of pilot-scale microbial IAA production. To reduce production costs in short-term fermentation, the basidiomycetous yeast *Rhodospiridiobolus fluvialis* DMKU-CP293 successfully generated IAA at a concentration of 3569.32  $\mu\text{g L}^{-1}$  within four days.

Production media in industrial processes plays a crucial role in green chemistry and environmental protection, which accounts for its high cost. An affordable medium made of lignocellulosic wastes may be a practical option. Under broth and immersed circumstances, Giri and Sharma (2020) used wheat straw to produce IAA. The nine folds' increase in the secretion of IAA following the pretreatment of wheat straw with *Phanerochaete chrysosporium* (150  $\mu\text{g mL}^{-1}$ ) was reported compared to untreated wheat straw (16.44  $\mu\text{g mL}^{-1}$ ).

The pretreatment of this abundant residue using white-rot fungi aimed at bioconverting the biomass (cellulose and hemicellulose) into readily fermentable sugars such as glucose to be used by strain *P. fermentans* or *P. chrysosporium* may for growth and IAA in tryptophan's presence (Giri and Sharma, 2020).

The agricultural industry could exploit these fungi-originated IAA and other phytohormones as a significant potential for large-scale production, with possible use in developing next-generation green fertilizers for farming applications.

Numerous microorganisms, including actinomycetes, can degrade lignocellulose and create IAA. Myo *et al.* (2019) observed that *Streptomyces fradiae* NKZ-259 produced the highest amount of IAA, 42.345  $\mu\text{g mL}^{-1}$ , in the presence of starch and  $\text{KNO}_3$ . Thus, by lowering the cost of producing these bio-compounds, their use in several significant agricultural cultivars becomes feasible. In a prior study conducted by Alloun *et al.* (2023), a native wheat rhizospheric strain *Streptomyces rubrogriseus* AW22 could achieve 188,290  $\mu\text{g mL}^{-1}$  using spent coffee grounds in optimized culture conditions.

**Table 1.** IAA microbial production using some agro-industrial wastes as carbon source

Agro-industrial waste	Main components	Strain	Reference
<b>Wheat straw</b>	Cellulose (30-40%) Hemicellulose (20-25%)	<i>Pichia fermentans</i>	Giri and Sharma (2020)
<b>Jatropha seed cake</b>	Carbohydrate (49%) Proteins (22%)	<i>Pleurotus ostreatus</i>	Bose <i>et al.</i> (2013)
<b>Wheat waste (leaves and roots)</b>	Cellulose and Hemicellulose	<i>Saccharothrix texasensis</i> MB15	Benadjila <i>et al.</i> (2022)
<b>Corn flour and soy bean meal</b>	Carbohydrate (66.2 %) + Proteins (10 %) Carbohydrate (18.6%) + Proteins (49.3%)	<i>Kasakonia pseudosacchari</i> TCPS-4	Chaudhary <i>et al.</i> (2021)
<b>Spent coffee grounds and carob beans power</b>	Spent Coffee grounds: Carbohydrates (40-50%) + Proteins (10-15%) + Carob: Carbohydrates (70-80%) + Proteins (4-8%)	<i>Streptomyces rubrogriseus</i> AW22	Alloun <i>et al.</i> (2023)

### *Bottlenecks in natural IAA commercialization*

Although bioproducts are essential, the market is currently developing slowly. This transformation is brought on by the fixed limitations placed on biopesticides. Registration for biopesticides is a labour-intensive, expensive process. On the other hand, their manufacture, which primarily relies on the fermentation procedure in industrial bioreactors, is complicated and related to issues such as contamination (Alloun *et al.*, 2023).

Microbial biopesticides require toxicological tests and the formulation of a stable product and their storage, which affect the cells' shelf life and survival rate. A solid policy network that can support these bioactive products is another impediment. Several nations demand thorough demonstrations of the product's pesticide capabilities across several seasons and all geographical locations (Alloun *et al.*, 2023).

Improving knowledge among farmers, manufacturers, and governmental organizations is a crucial problem that can be resolved. Lack of resources and a lack of confidence between producers and regulators are two other grave problems. A better comprehension of the mechanisms by which biopesticides work may increase public awareness of the advantages of sustainability.

### **Actinobacteria as plant growth promoters and auxin producers**

The ability to produce physiologically active compounds, such as PGP substances, and their significant capacity to synthesize auxin (Alloun *et al.*, 2023). IAA production was attributed to both *Streptomyces* and non-*Streptomyces* species. Nevertheless, compared to other bacterial species associated with plants, concentration ranges are still moderate. Actinobacteria have been reported to stimulate the growth of many crop plants actively.

For instance, Toumatia *et al.* (2016) detected wheat seedling stimulation and enhanced shoot growth after inoculation with Saharan soil-originated *Streptomyces mutabilis* IA1. The protection against pathogenic *Fusarium culmorum*, causing agent of seedling blight, has also been reported.

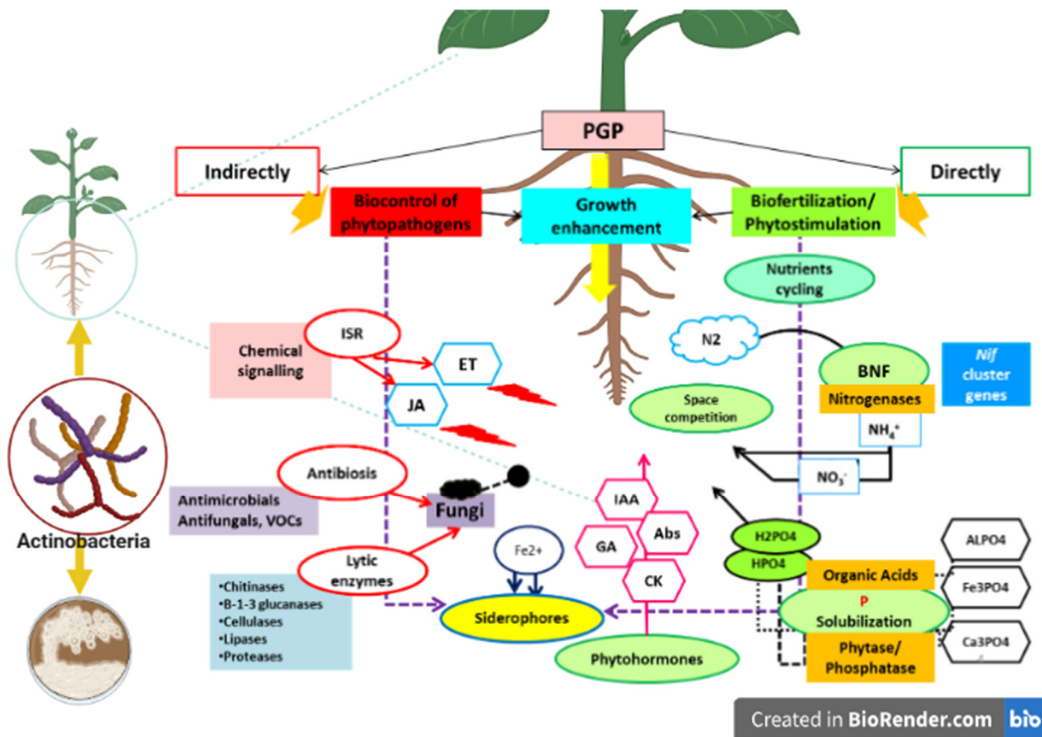
The PGP effect of Actinobacteria may be related to their capability to produce a wide array of secondary metabolites, including phytohormones, lytic enzymes, and antimicrobials. Hence, the merit behind this positive effect on plant growth is related to the cooperation of more than one mechanism rather than a single trait result.

Actinobacteria strains synthesize lytic enzymes. Some of these enzymes contribute to the mineralization of organic matter by dissolving complex natural polymers like lignocellulose (cellulose, hemicellulose, and lignin). Meanwhile, chitinases take part in the degradation of fungal cell walls (Alloun *et al.*, 2023).

Figure 2 demonstrates the mechanisms by which Actinobacteria boost plant growth and the immune system and protect pathogenic microorganisms, which constitute the multifunctionality of these filamentous bacteria.

Antagonistic *Streptomyces* species are known to share the ability to produce IAA. For instance, Abbasi *et al.* (2019) demonstrated a positive correlation between the PGP antagonistic *Streptomyces* strains and their biocontrol abilities against tomato *Fusarium* wilt caused by *F. oxysporum* Schlecht. f. sp. *Lycopersici* (Sacc.), between siderophore and IAA synthesis, siderophore accumulation, and growth inhibition.

Therefore, these authors hypothesized that other properties, such as siderophore synthesis, are crucial in promoting plant growth and that IAA production alone does not drive plant growth.



**Figure 2.** Multi-functionality role of Actinobacteria including direct and indirect mechanisms for plant growth promotion

The synergistic effect of numerous PGPR traits also contributed to the improvement of plant development. Due to their incapacity to produce siderophores, IAA-producing antagonistic isolates did not promote several vegetable species' growth, as Kunova *et al.* (2016). Nine of the fourteen actinomycetes strains discovered in saltwater (Sebkha) in northeastern Algeria were able to produce IAA at varying rates (Djebaili *et al.*, 2020).

Moreover, a study by Borah and Thakur identified around 46 endophytic actinobacteria related to *Camellia* species (Borah and Thakur, 2020). Actinobacteria from nine different genera, displayed PGP features *in vitro*. The selected three potent isolates were discovered to promote the growth of various tea clones in nursery circumstances during seedling bioassays. They could degrade a variety of substrates. In addition, the Actinobacteria strains obtained from Moroccan desert soils explored the production of IAA due to their critical roles in promoting plant growth (Boubekri *et al.*, 2021). The rooting process is induced by auxin, from emergence through elongation.



**Table 2.** Recent reports on Actinobacteria strains possessing plant growth promotion activities

Actinobacteria strain	Origin/host plant	Strain features and effects on plant	Reference
<i>Streptomyces mutabilis</i> IA1.	Saharan soil, Algeria	Wheat Seedling growth stimulation and biocontrol properties against <i>Fusarium culmorum</i> . Decreased disease occurrence (64.7%) and severity (79.6%). Colonization of internal plant roots tissues and caryopsis. Phytohormones production (IAA).	Toumatia <i>et al.</i> (2016)
<i>S. rochei</i> PTL2	Root tissues of <i>Panicum turgidum</i> , a Saharan native plant in Algeria	<i>In vitro</i> antifungal activities against <i>R. Solani</i> <i>R. solani</i> damping-off incidence from 89.3% to 14.1% when seeds were treated with talcum powder formulation based on this strain compared to chemical seed treatment with Thiram® provided a disease incidence of 16.7%. Phytohormones production. Plant growth promotion and a significant ( $P < .05$ ) improvement in tomato seedling's root and shoot growth.	Zamoum <i>et al.</i> (2017)
<i>Streptomyces</i> sp.	Rhizosphere soil of cucumber and tomato	IAA and siderophore production. <i>In vitro</i> antagonistic effect against <i>Fusarium wilt</i> of tomato caused by <i>F. oxysporum</i> Schlecht. f. sp. <i>lycopersici</i> (Sacc.) race 3. Positive correlation between antagonism and PGP activities in the featured strain.	Abbasi <i>et al.</i> (2019)
<i>Nocardiopsis aegyptica</i> H14, <i>Nocardiopsis dassonvillei</i> subsp. <i>dassonvillei</i> T45, <i>Streptomyces xantholiticus</i> G22 and <i>Streptomyces iakyrus</i> G10	Salty water (Sebkha) in Northeast of Algeria	IAA production. Biocontrol of tomato pathogens <i>F. solani</i> Phosphate solubilisation and lytic enzymes production. Promotion of tomato plants growth.	(Djebaili <i>et al.</i> (2020) (Smati & Kitouni, 2019)
<i>Streptomyces</i> (60.8%), <i>Nocardia</i> (13.0%), <i>Actinomadura</i> and <i>Kribbella</i> (6.5%), <i>Microbispora</i> (4.3%), <i>Amycolatopsis</i> , <i>Pseudonocardia</i> , <i>Saccharomonospora</i> and <i>Rothia</i> each (2.1%)	Endosphere of <i>Camellia</i> spp. and related genera, Eurya	PGP characteristics <i>in vitro</i> . Enhancement of tea clones' growth in nursery conditions during seedlings bioassays by the selected three potent isolates.	Borah & Thakur (2020)
<i>Actinoplanes deccanensis</i> UAE1 and <i>Streptomyces euryhalinus</i> UAE1	Dwarf glasswort rhizosphere ( <i>Salicornia bigelovii</i> Torr.)	Production of putrescine, Spermidine, and Spermine, IAA and gibberellic acid production. Increased shoot and root lengths and dry weights, as well as seed yields.	El-Tarabily <i>et al.</i> (2020)

<i>Arthrobacter arilaitensis</i> strain MG547869 and <i>Streptomyces pseudovenezuelae</i> MG547870	Maize plantations ( <i>Zea mays</i> L.)	IAA/Siderophore production and P solubilisation, Ammonia & HCN production, ACC desaminase activity. Improved seedlings emergence and growth Increased shoot and root lengths, germination % and vigor index. Increased dry shoot and root biomass and chlorophyll content.	Chukwuneme <i>et al.</i> (2020)
<i>Streptomyces griseorubens</i> BC10	Moroccan desert soils	IAA produces and stimulates plant growth by inducing the rooting process from emergence to elongation.	Boubekri <i>et al.</i> (2021)
<i>S. rubrogriseus</i> AW22	Wheat rhizosphere, Algeria	<i>In vitro</i> IAA production. Lytic enzymes (chitinases, proteases, laccases, catalase, cellulase).	Alloun <i>et al.</i> (2023)

### Bioinformatics for the selection of auxin-producing Actinobacteria

Computer science innovations and DNA sequencing, such as Next Generation Sequencing (NGS), can adequately describe the rhizosphere and endophyte population composition without any bias imposed by microbial culture and enable the acquisition of metagenomic data illustrating the taxonomic profile of the relevant microbial community and their activities. The high dimensionality of the data associated with noise and sparse data sets may complicate the investigation of the metagenomic microbial community to become a time-consuming task. Machine learning approaches may also offer solutions to dimensional data analysis regarding the microbial strain's genetic characteristics, their metabolic pathways, and the relationship between productivity and environmental variables.

Global and targeted genomics are the two main approaches that constitute genomics. While the first attempts to sequence the entire genome, the targeted technique focuses on sequencing a single gene, 16S rRNA as an example, followed by sequences screening to provide their taxonomy designations using the close-reference method and the *de novo* strategy. Shotgun sequencing in global metagenomics entails cutting genomes into small fragments so that a high-throughput sequencer can sequence them.

The de Bruijn Graph (DBG) approach and Overlap / Layout / Consensus (OLC) is the most common metagenomic sequences assemblers for genome reconstruction. QUAST can assess the genome assemblies with or without the reference genome. Velvet, SOAP, and Megahit are the most common metagenomic assemblers.

DIAMOND and MEGAN compare DNA sequencing reads with protein reference sequences like NCBI-nr. MG-RAST employs BLAST to categorize metagenomic sequences into various class units. Marker genes are used as references for binning in other programs, including MetaPhlan3, PhyloSift, AMPHORA2, and MetaPhyler (Beghini *et al.*, 2021). MEGAN and DIAMOND's output serves for taxonomic and functional analysis.

Actinobacteria's genome annotation in databases needs to be completed and consists of numerous fragments with inadequate annotation. The ActDES program offers a controlled database of 612 actinobacterial genomes from 80 genera. This database requires a version of Bioconda with BLAST, MUSCLE, GBLOCKS, hmmer, and quicktree installed. Some of the files' formats can be changed using the hmmer. Alignments and sequence cleaning require MUSCLE and GBLOCKS. A phylogenetic tree can be created using the MEGAX program, the neighbour-joining (NJ) method based on the Tamura Nei model, and a bootstrap analysis involving 1000 replications. Further, the BLAST search tool compares query sequences to the ActDES database.

## Conclusions

Actinobacteria strains, which are associated with roots, have been examined for their ability to release auxin. Through their flexible and balanced interactions with secreted secondary metabolites and their ability to interact with other hormones, auxins regulate various developmental processes, making them the key player in controlling stress tolerance responses. Actinobacteria may be essential and dominant in their host rhizosphere as plant inoculants. In addition to synthetic auxin, these strains may be fascinating metabolic engineering targets for the induction of upregulation and host tolerance to abiotic stresses. Although numerous reports on effective actinobacteria isolates have demonstrated their ability to biocontrol plant diseases (biopesticide effect) and PGP potential (biostimulation or bio-fertilizing impact), these strains still need to be properly explored and made available for large-scale production and sale.

## Authors' Contributions

W. ALLOUN wrote the first draft of the manuscript, contributed to the conception and design, and revised the article; S. CHAOUA, H. KECIES, H. DJELID and B. CORNU contributed to writing the first draft; M. GARES contributed to revising the draft; N. KACEM CHAOUICHE supervised and approved the version to be submitted for publication.

All authors read and approved the final manuscript.

## Ethical approval (for researches involving animals or humans)

Not applicable.

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## Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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