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The Role of Auxins in Interactive Relationships between Plants and Pathogens.

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ABSTRACT
This study aimed to elucidate the importance of plant hormones regulating plant growth, especially auxin (indoleacetic acid). The study showed that this hormone is produced by both plants and microorganisms such as bacteria and fungi through different metabolic pathways, yet they produce the same auxin. The amino acid tryptophan is a primary source in the biosynthesis of indoleacetic acid. Research has shown the role and effectiveness of auxin in plants, as well as its role in the interactions between plants and pathogens, and its effect on pathogens varies positively or negatively. It is important in the symbiotic relationships between root nodule bacteria and plants and mycorrhizae and plants that promote plant growth and increase its resistance to pathogens. Additionally, auxin influences the growth and pathogenicity of plant pathogenic fungi and increases the pathogenicity of fungal pathogens.

***Keywords*:** Indoleacetic acid, plant hormones, tryptophan.

INTRODUCTION

Plant hormones are organic chemical substances that regulate plant physiological processes and have significant effects in small quantities. They play important roles in cell elongation in leaves, stems, and roots, as well as in cell differentiation, division, germination, dormancy, leaf and fruit abscission [1; 2; 3]. Growth regulators work by stimulating the synthesis of messenger RNA molecules, leading to the formation of specialized enzymes that regulate plant physiology. Plant hormones are divided into auxins, gibberellins, cytokinins, abscisic acid, and ethylene gas, which can be distinguished by their chemical structure and biological activity. Additionally, many other hormone-like compounds have been discovered, such as brassinosteroids, jasmonate, salicylic acid, nitric oxide, and strigolactones [4; 5]. Hormones are present in plant tissues, where more than one hormone may be found in a single tissue. Hormones are characterized by their action within the same cell or by their ability to move to another location and exert their effects there. They are naturally occurring, but when synthesized chemically, they are called growth regulators [6]. The effects of hormones differ; auxins and gibberellins, for example, promote stem elongation [7; 8], but their mechanisms of action vary. On the other hand, abscisic acid and ethylene inhibit stem growth, dividing them into two groups: growth promoters, which stimulate plant growth, such as auxins, gibberellins, and cytokinins [9]. The second group consists of growth inhibitors represented by abscisic acid and ethylene [10; 5]. Hormones cannot be judged as stimulatory or inhibitory without considering the concentration used; they become growth inhibitors when used at high concentrations. Additionally, different plant organs vary in their response to the same hormone depending on the plant's growth stages and plant species. Hormones may have cumulative, cooperative, or antagonistic effects, depending on their individual impacts. Therefore, plant growth and development result from the combined effects of various hormones present in the plant. Furthermore, these hormones can be utilized as natural antimicrobial agents, thereby reducing the environmental impact of pesticides and promoting the development of resistant individuals [11]. Hormones are present in angiosperms, gymnosperms, ferns, bacteria, algae, and fungi [12; 13; 14], and they are also produced by beneficial microorganisms inhabiting the rhizosphere, similar to those produced by plants [15].

Auxins (Indoleacetic Acid)

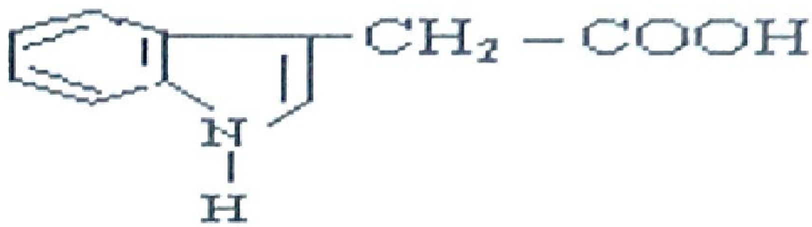
Auxins were the first plant hormones to be discovered and studied, and they play a significant role in most quantitative growth changes that occur throughout the plant's life cycle [16]. They also stimulate plant defence mechanisms against environmental stresses by affecting rhizosphere interactions, root thickness, and number, increasing plant nutrient and mineral uptake, and promoting plant growth [17; 18]. The credit for the discovery of the first auxin, Indol-3-acetic acid (IAA), in oat plants goes to the American Scientist Went in 1926[19]. It was found that the apex of the coleoptile secretes auxin, which leads to its elongation. It is believed to move dynamically from areas of high concentration, such as the shoot apex, to areas of low concentration or those completely devoid. This movement starts from the shoot apical meristem and ends at the lower base of the root system in upright plants. In horizontal or prostrate plants, auxins move from the upper side of the stem and root to their lower side, causing the plants to bend as they elongate and grow.

Many molecules similar to auxin have been discovered in plants, including 4-chloroindole-3-acetic acid, indole-3-butyric acid, and phenylacetic acid, as well as synthetic compounds like dichlorophenoxyacetic acid and naphthalene-1-acetic acid, which exhibit biological activity similar to auxin [20].

The word "auxin" is derived from the Greek word meaning "growth" [21]. Auxin plays a crucial role in plant physiology, contributing to cell division, elongation, differentiation, fruit development, and phototropic responses [22]. Additionally, it plays an important role in stimulating plant defences against environmental stresses by influencing tryptophan metabolism, root thickness and number, increasing plant nutrient and mineral uptake, and promoting plant growth [23; 24]. Levels of auxin are often high in many diseased plants, despite some pathogens reducing auxin levels in the host. This is because certain pathogens have the capability to produce auxin themselves, such as the fungus *Plasmodiophora brassica*, *Fusarium oxysporium*, and *Phytophthora infestans*. In some diseases, like black stem rust, auxin levels are elevated due to reduced breakdown of auxin caused by inhibition of auxin oxidase enzyme responsible for auxin degradation. Increased levels of auxin lead to increased elasticity of cell walls, thereby facilitating the breakdown of pectin, cellulose, and proteinaceous cell wall components by enzymes secreted by the pathogens.

Chemical Structure Of Indole Acetic Acid

Indole-3-acetic acid (IAA) has a chemical structure composed of a carboxylic acid group attached to a benzene ring at the C-3 position of the indole ring. It is a colourless solid substance that is soluble in polar organic solvents.



Auxin can be produced through multiple pathways. According to the following pathways, the amino acid tryptophan serves as a primary source in the biosynthesis of indole-3-acetic acid (IAA), which is produced through a series of reactions in the tryptophan-dependent pathway. In this pathway, tryptophan is first converted to indole pyruvic acid, and then to indole-3-acetaldehyde, which further oxidizes to IAA. Alternatively, tryptophan can be converted to tryptamine, which is then transformed into indole-3-acetaldehyde, which oxidizes to IAA [25]. Many pathways have been described [26; 27].

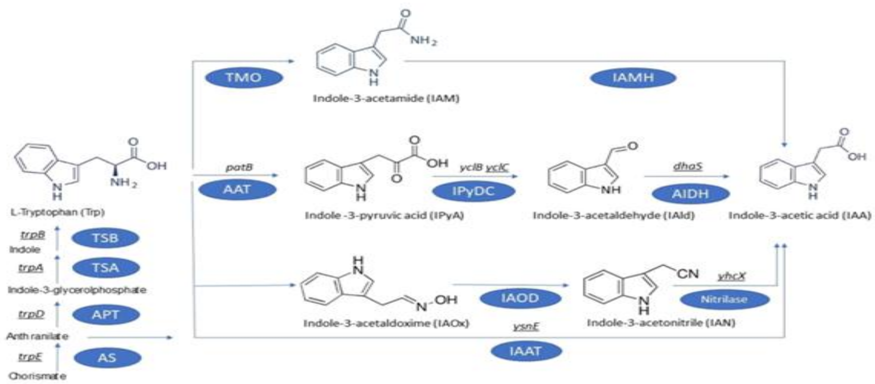
In the IAN pathway, the amino acid tryptophan is directly converted to Indole-3-acetaldoxime (IAOX). This compound then undergoes the formation of Indole-3-acetonitrile (IAN) through enzymatic action, facilitated by nitrilases. Subsequently, IAN is converted to Indole-3-acetic acid (IAA).

In the TAM pathway, the process begins with the removal of a carbon atom through decarboxylation from tryptophan, forming the compound Tryptamine (TAM). TAM then undergoes a series of enzymatic reactions to form Indole-3-acetaldehyde (IAAID). Subsequently, IAAID is oxidized by the enzyme dehydrogenase to form auxin (IAA).

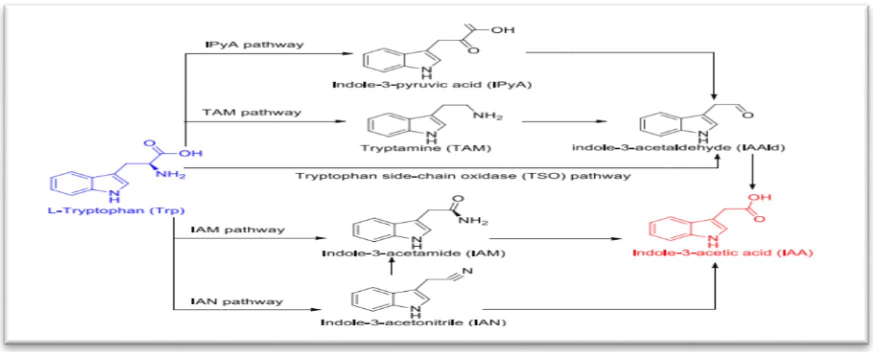
In the IPA pathway, amino groups are extracted from the amino acid tryptophan, resulting in the formation of Indole-3-Pyruvate (IPA). A carbon atom is then removed from IPA to form Indole-3-acetaldehyde (IAAID). IAAID is subsequently transformed into auxin (IAA) by the enzyme Aldehyde oxidase.

In the IAM pathway, the amino acid tryptophan is utilized to produce the intermediate compound Indole-3-acetamide (IAM) through the enzymes Trp.monooxygenase and xAM hydrase. The auxin produced from bacteria typically induces morphological changes in the host plant.

Bacteria such as *Bacillus sp.*, *Pseudomonas sp*., *Azospirillum s*p., *Enterobacter sp.*, and *Serratia sp*. are known to produce auxin. This auxin is synthesized from tryptophan, which is converted to indole-3-acetamide by the enzyme tryptophan-2-monooxygenase. Indole-3-acetamide then undergoes hydrolysis in water to form auxin, similar to plant-produced auxin but through slightly different biosynthetic pathways. These pathways include indole-3-pyruvic acid, indole-3-acetamide, and indole-3-acetonitrile. Additionally, auxin can be synthesized independently of tryptophan. Auxin is synthesized in apical tissues of aerial parts such as young leaves and terminal buds, as well as in the growing tips of roots of certain plant species, fruits, and seeds. In fungi like *Fusarium sp*., *Colletotrichum gloeosporioides*, *Ustilago*, and *Rhizoctonia*, auxin production occurs as well [28; 29]. The production of auxin is influenced by environmental factors such as pH, temperature, osmolarity, and carbon availability ،demonstrated that water-soluble vitamins at low levels affected the production of indole-3-acetic acid by bacteria, indicating that carbon and nitrogen sources are important factors for the production of fungal and bacterial indole-3-acetic acid. [30] mentioned that the optimal production of indole-3-acetic acid from fungi occurs at 28°C.



The biosynthesis of indole-3-acetic acid [31]



The biosynthesis of indole-3-acetic acid [32]

The role and importance of auxins for plants include:

1. Increasing water absorption rate.
2. Enhancing respiration rate.
3. Playing a role in protein and nucleic acid synthesis.
4. Directing the movement of nutrients.
5. Influencing cell division.
6. Stimulating cell elongation and expansion.
7. Promoting the formation of lateral and adventitious roots.
8. Affecting membrane permeability.
9. Inducing positive phototropism in shoot tips and positive geotropism in roots.
10. Playing a role in apical dominance phenomenon

Auxin Transport Through Plants

The auxin movement within plants is polar, moving from the base to the tip in stems and from the tip to the base in roots. This polar movement of auxin is known as basipetal transport in the stem and acropetal transport in the root. Auxin transport occurs from regions of high concentration to regions of lower concentration, primarily through the parenchyma cells adjacent to the vascular bundles. The process relies on energy generated from metabolic activities and the oxygen concentration in tissues. It has been observed that the process increases with higher oxygen concentration. Additionally, the efficiency of auxin transport is influenced by the age of plant tissue.

The role of auxins in interactions between plants and pathogens

Many interacting and non-interacting fungal species produce volatile compounds, iron carriers, and hormones (Figure 4) that affect plant growth in different forms [33].

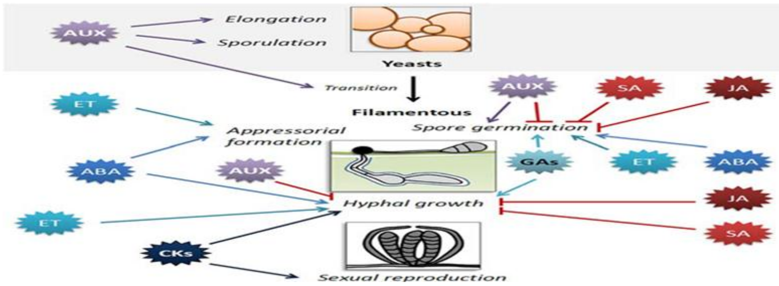


Figure 4. Effect of hormones on fungi [34]

Auxins can have both positive and negative effects on plant growth, and they can either increase or decrease susceptibility to pathogenic organisms. Auxins play a crucial role in activating plant defense responses, which is evident when plants are infected by fungi such as Botrytis, Rhizoctoina, and Alternari*a*. Auxins levels typically rise upon infection, and external application of Auxins has been shown to reduce disease incidence [35]. [36] demonstrated that auxin reduces the germination of *Fusarium oxy*sporum *lycopersici*, the causal agent of Fusarium wilt in tomatoes. [37] reported that auxin production leads to morphological changes and fungal hyphal growth in *Saccharomyces cerevisiae* and *Candida albicans*. [38] found that low concentrations of auxin increased the growth of *F. delphinoides*, which affects chickpeas, while high concentrations decreased growth. Therefore, the effects of auxin on fungal physiology vary depending on the fungal species and auxin concentration.

[39] clarified that auxin stimulates tumor formation on plants when infected with bacteria such as *Agrobacterium tumefaciens* and *Pseudomonas savastanoi*, and auxin increases their severity. Auxin plays a role in the relationship between nitrogen-fixing bacteria and plants, encouraging nodule formation [40] and increasing root length, number of root hairs, and lateral roots, thereby enhancing nutrient uptake [41]. [32] demonstrated that rhizobacteria synthesize indole acetic acid to promote plant growth, as an increase in tryptophan secretion by plant roots was observed in the presence of bacteria, stimulating auxin production [42]. Additionally, auxin is important for mycorrhizae [43]. [44] demonstrated that the fungus *Penicillium sp*., which produces indole acetic acid, enhanced sesame plant growth and suppressed *Fusarium sp.* infection. [45] reported that the fungus Trichoderma, producing indole acetic acid, reduced *Ralstonia solanacearum* infection in tomato plants. [46] mentioned that inoculating *Zea mays* plants with the fungus *Candida tropicalis* led to an 85% improvement in grain quality compared to the control treatment. Additionally, there was a 40% and 24% increase in root and shoot lengths, respectively, in wheat seedlings treated with *Mortiella species* producing indole acetic acid [47]. [48] and [49] stated that auxin enhances the ability of the fungus *Hebeloma cylindrosporum* to invade the root tissues of *Pinus pinaster* plants. Furthermore, auxin levels accumulate upon plant infection with Fusarium, as it stimulates genes to produce auxin, thereby increasing the severity of the fungus [50]. [51] elucidated that the fungus *Colletotrichium gloeosporioides* f.sp. *aeshynomene* produces auxin during early stages of plant colonization. [37] demonstrated that indole acetic acid promotes the growth of fungal hyphae in *Candida albicans* and *S. cerevisiae*, thereby increasing their virulence. These findings indicate that auxin plays a significant role in fungal diseases affecting plants and the pathogenicity of causal agents [52]. [53] demonstrated the ability of the fungus *Aspergillus awamori* to colonize maize seedling roots compared to the control treatment, resulting in improvements in seedling metrics attributed to increased production of indole acetic acid. [54] further clarified that inhibiting the synthesis of indole acetic acid reduced *Fusarium oxysporum* colonization of maize roots by 46% to 62% in successive applications on leaves and roots. Conversely, an increase in indole acetic acid synthesis enhanced Fusarium colonization of seedlings, leading to increased growth metrics such as root and stem length, fresh and dry weight, and chlorophyll content. [14] Noted an increase in protein content upon application of indole acetic acid secreted by *Pleurotus* fungus, ranging from 10.62 to 13.17 mg/g compared to the control treatment, which was 9.24 mg/g, along with increases in root and stem length, as well as fresh and dry weight of wheat plants.

[21] described the mechanisms by which ethylene increases fungal pathogenicity through the hormone indole acetic acid produced by the former. The first mechanism involves indole acetic acid inhibiting the defense signals dependent on salicylic acid, which affects the cell wall and stomata. The second mechanism entails indole acetic acid stimulating internal production of indole acetic acid in plants, enhancing the detrimental effects of fungi that produce indole acetic acid. Plants and fungi can communicate through signals of indole acetic acid, with concentrations of this hormone regulating the relationship between fungi, either stimulating or inhibiting it. Different fungi have optimal thresholds for levels of indole acetic acid affected by varying conditions, making it an important factor in fungal competition.

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دور الاوكسينات في العلاقات التفاعلية بين النباتات والمسببات المرضية (مقالة مراجعة)

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الخلاصة

هدفت هذه الدراسة الى بيان أهمية الهرمونات النباتية المنظمة لنمو النبات وخصوصا هرمون الاوكسين (اندول حامض الخليك) ،اذ بينت الدراسة ان هذا الهرمون ينتج بالنبات والاحياء الدقيقة مثل البكتريا والفطريات وعن طريق مسارات تفاعلية مختلفة لكنها تنتج نفس الاوكسين اذ يعد الحامض الأمينى Tryptophan مصدر أساسي في عملية بناء الاندول حامض الخليك وأوضحت الأبحاث دور وفعالية الاوكسين بالنسبة للنبات فضلا عن دوره خلال العلاقات التفاعلية بين النبات والمسببات المرضية واختلاف تأثيره على المسببات المرضية ايجاباً او بشكل سلبي اذ انه مهم في العلاقات التعايشية بين بكتريا العقد الجذرية والنبات والمايكورايزا والنبات التي تعزز نمو النبات وزيادة مقاومته للمسببات المرضية فضلا عن تأثير الاوكسين في نمو وتجرثم الفطريات الممرضة للنبات وزيادة امراضية المسببات المرضية الفطرية.

الكلمات المفتاحية : اندول حامض الخليك ، هرمونات نباتية ، Tryptophan