

Phytohormones and Plant Growth Regulators - A Review

Carlos E. Agudelo-Morales ^{1,3}*, Tulio A. Lerma ^{1,2}, Jina M. Martínez ^{1,2}, Manuel Palencia ², Enrique M. Combatt ⁴

¹ Mindtech Research Group (Mindtech-RG), Mindtech S.A.S., Montería/Barranquilla – Colombia.

² Research Group in Science with Technological Applications (GI-CAT), Department of Chemistry, Faculty of Natural and Exact Sciences, Universidad del Valle, Cali – Colombia.

³Department of Biology, Laboratory of Microscopy, Universidad Nacional de Colombia. Cr 32 # 12-00, Palmira – Colombia.

⁴ Department of Agricultural Engineering, Faculty of Agricultural Science, Universidad de Córdoba, Monteria-Colombia.

Corresponding Author: Carlos E. Agudelo-Morales. E-mail: c.agudelo@mindtech.com.co

Graphical Abstract



Abstract. In plants, diverse physiological processes of adaptation and survival are a result of varied and complex processes of chemical and physical reactions, mediated by chemical compounds called plant hormones. Within this group of chemical substances are the "classical phytohormones" like Auxins, Gibberellins, Cytokinins, Ethylene, Abscisic acid; but also, signaling molecules including Brassinosteroids, Jasmonic acid, Salicylic acid, Strigolactones, Systemin Peptides and Nitric Oxide, among other, and which are functionally analogous to plant hormones, play an important role in agricultural activities. In agriculture, plant growth regulators can promote crop development and their productivity, stimulate rooting cuttings, breaking dormancy in fruits, promote flowering, accelerate or delayed ripening, control plant development, increase ramification, suppress shoot growth; but also, due to their origin, structural richness and their natural influence on biological processes, the knowledge of these biochemical entities and their properties are a promising alternative to advance in the development of more sustainable strategies for the production of food, goods and services. The aim of this review is to provide a conceptual platform, functionality, and potential uses of plant hormones in different technological fields, including agriculture, medicine, biotechnology, and food industry, as well as the different biosynthesis routes defined so far.

Keywords: Abscisic acid, ethylene, brassinosteroids, cytokinins, gibberellin, strigolactones, plant peptide hormones, jasmonic acid, salicylic acid.

Cite as: Agudelo-Morales C.E., Lerma T.A., Martínez J.M., Palencia M., Combatt E.M. Phytohormones and Plant Growth Regulators - A Review. J. Sci. Technol. Appl. 10 (2021) 27-65. https://doi.org/10.34294/j.jsta.21.10.66

| Accepted: 2021-05-12 | Published: 2021-05-15 | Paper Number: 066 | Review |
|----------------------|--|--|-------------------------------|
| | IC-SA 4.0 This is an open access a Creative Commons Atribu | article distributed under the terms of the attion License | © MT-Pallantia Publisher 2021 |

Program Mindtech for Scientific Knowledge Diffusion (PMSKD since 2016) | Barranquilla - Colombia | ISSN from DIMAT-Universidad de Concepción, Concepción - Chile

Content

1. Introduction 2. Metabolic regulators of plants 3. Plant growth regulators 4. Phytohormones 4.1 Auxins (AUXs) 4.1.1 Biosynthesis of auxins 4.1.2 Applications of auxins 4.2 Gibberellins (GBRs) 4.2.1 Biosynthesis of Gibberellin 4.2.2 Applications of Gibberellins 4.3 Cytokinins (CTKs) 4.3.1 Biosynthesis of Cytokinins 4.3.2 Applications of Cytokinins 4.4 Ethylene (ETH) 4.4.1 Biosynthesis of ETH 4.4.2 Overview applications of Ethylene 4.5 Abscisic acid (ABSAc) 4.5.1 Biosynthesis of Abscisic acid 4.5.2 Overview applications of Abscisic acid 4.6 Brassinosteroids (BRSTs) 4.6.1 Biosynthesis of Brassinosteroids 4.6.2 Applications of Brassinosteroids 4.7 Jasmonic acid (JMAc) 4.7.1 Biosynthesis of Jasmonic acid 4.7.2 Applications of Jasmonic acid 4.8 Salicylic acid (SLAc) 4.8.1 Biosynthesis of Salicylic acid 4.8.2 Applications of Salicylic acid 4.9 Strigolactones (STGLs) 4.9.1 Biosynthesis of Strigolactones 4.9.2 Overview applications of Strigolactones 4.10 Plant peptide hormones (PPHs) 4.10.1 Biosynthesis of plant peptide hormones 4.10.2 Applications of plant peptide hormones 4.11 Nitric oxide (NO) 4.11.1 Biosynthesis of Nitric oxide 4.11.2 Applications of nitric oxide 5. Conclusions and perspectives 6. References

1. Introduction

In the higher plants, the regulation, coordination of metabolism, growth, and morphogenesis efficiently depend on chemical signals produced by the plant itself. In the 19th century many of our current concepts about intercellular communication in plants were derived from research conducted in animals and hence the analogy of some terms and concepts. In animals the chemical messengers mediating intercellular communication are called hormones (Greek Hormaein = to stimulate), whereas in plants, growth and other physiological functions are mediated by chemical messengers called plant hormones or phytohormones. The term phytohormone is strictly



Agudelo-Morales C.E., et al., J. Sci. Technol. Appl. 10 (2021) 27-65. DOI: 10.34294/j.jsta.21.10.66 ISSN: 0719-8647 | Available: www.jsta.cl

used to name the compound chemicals synthesized inside the plant, which can be transferred and used in specific physiological communication processes, not including substances of xenobiotic origin. However, the terms plant growth regulators and phytohormone are sometimes often used analogously (Overbeek, 1944; Rademacher, 2015).

Plants can generate phytohormones that regulate shoot growth, root growth, flowering, leaf abscission, fruit ripening, and many other metabolic processes. In general, the most important hormones used in vegetative propagation of plants are Auxins (AUXs), Cytokinins (CTKs), Gibberellins (GBRs), Abscisic acid (ABSAc), and Ethylene (ETH), which promote root growth, cell growth, and stem elongation, among others. However, through science and technology progress, new chemical compounds exhibiting the properties of plant hormones have been discovered in recent years (Hasan et al., 2018; Gancheva et al., 2019). Besides natural phytohormones, it is possible today to find synthetic and biotechnological commercial products, referred as plant growth regulators, which are well known for their regulatory effects (Andresen and Cedergreen, 2010). Thus, plant growth stimulators are synthetic, biological, biosynthetic substances, or systems, able to produce an effect on plants; some examples are naphthalene acetic acid, or ANA, which is a root growth promoter (Ortolá et al., 1991; Sanower and Urbi, 2016) and bacterial inoculate able to contribute with the nitrogen fixing and the strengthening of the rhizosphere (Tsavkelova et al., 2006; Garces et al., 2017; Lerma et al., 2018).

The uses of these chemical compounds in the development of the agricultural industry are of great importance to food security, the stable supply of agricultural products and the subsequent employment generation; in this regard, the global plant growth regulators market size, including auxins and cytokines, was estimated to be valued at \$5.72 billion in 2019 and is assumed a compound annual growth rate of 8.5% during 2020 to 2027, mainly in fruit and vegetable crops, oilseeds, cereals, legumes, among others (Fiormarkets, 2020). Moreover, in recent years there has been a growing interest on the part of medicinal chemistry for biological activity of small molecules on plants, including some plant hormones, in search of new areas of economic and scientific development (Hayes and Bleakley, 2018; Hasan et al., 2018).

In this way, due to their origin, structural richness and their natural influence on biological processes, the knowledge of these biochemical entities and their properties, phytohormones, plant growth regulators, and plant-signaling molecules are a promising alternative to advance in the development of more sustainable strategies for the production of food, goods and services. By the above, it is important to advance toward the knowledge of these substances, design new strategies and approach for expanding their potential uses. The primary aims of this review are: (i) Exploring the conceptual frameworks that have been proposed to support research in the field of plant growth regulators, (ii) providing the main background and current state of research about plant growth regulators and their biosynthetic pathways, and (iii) highlight new approach and applications of phytohormones in fields such as medicine, biotechnology and the food industry.

2. Metabolic regulators of plants

Different physiological processes (metabolism) of plants such as nutrition, absorption, circulation, transpiration, photosynthesis, respiration, growth, flowering, fruit ripening, rooting, among many others, are in fact a varied and complex process of chemical reactions and physical events. Plants are always adapting to their environment in order to ensure their survival and viability. In these pathways and gradients, chemical messengers play an important role in growth, stress response and homeostasis (Jaillais and Chory, 2010). Within the metabolism of plants, diverse groups of chemical compounds can be identified, classified according to their function as primary metabolites, secondary metabolites and plant hormones (see Figure 1). Primary metabolites are directly related to growth and they are conserved by the plant (e.g., amino acids, nucleotides, sugars, lipids, fatty acids, among others). Secondary metabolites include a wide number and variety of compounds with a wide structural richness such as phenolic compounds, terpenes, and nitrogen-containing chemical groups like alkaloids, which are produced at very low concentrations. These substances emerge from biochemical processes which are not directly related with the survival of the plants, for this reason, it is accepted that their production is associated to one "secondary metabolism" and in this way to differentiate it from those metabolic processes essential for the life of plants. Finally, plant hormones are secondary metabolites, which can be defined as small molecules that regulate plant processes, including the production of other metabolites, by interacting with receptor proteins, leading the coordination of

physiological processes inside and outside the cells and tissues (Taiz and Zeiger 2003; Davies, 2010; Erb and Kliebenstein, 2020).

3. Plant growth regulators

Plant growth regulators, or phytoregulators, are chemical compounds acting as plant-originated bioregulators able to produce effects similar to those caused by phytohormones. They are exogenous sourced through and their supply is specific purposeful that is usually related to productive goals. In agriculture, regulators can promote plant development and productivity, stimulate rooting of cuttings, inhibit seed dormancy, promote flowering, accelerate or delay fruit ripening, control plant development, increase branching, suppress shoot growth; for example, in weed management for crops, harvest, reforestation, phytoremediation activities, in vitro testing, among many other purposes (Overbeek, 1944; Rademacher, 2015). Note that the main difference between the concepts phytohormone and phytoregulators is the xenobiotic origin of the latter. Therefore, strictly speaking, if a phytohormone is synthesized, either by chemical or biotechnological methods, and subsequently used to promote a response different from that which is naturally expected from its biosystem of origin, the most appropriate name for this biomolecule is phytoregulator (for an effect on plants) or bioregulator (for an effect on the metabolism of living organisms). Thus, it is understood that the phytohormone concept is limited to a specific context, while the phytoregulator and bioregulator concepts are broader in their meaning, in that order (see Table 1).



Figure 1. Illustration of main primary metabolites, secondary metabolites and plant hormones identified in plants.

| Туре | Description | Typical applications | Example |
|---------------|--|---|--------------------------------|
| Phytohormones | This term describes chemical substances | Interruption of the latency period of seeds, induction of | Auxin, Gibberellin, Cytokinin, |
| | synthesized by the plants themselves in order to | fruit development, regulation of longitudinal growth of | Abscisic acid, Ethylene, |
| | perform diverse functions related to growth and | the stem, regulation of photosynthesis, senescence, | Brassinosteroids, Jasmonic |
| | development of plants. | apoptosis (programmed death), resistance to | acid, Salicylic acid. |
| | | pathogens, among others. | |
| Plant Growth | These are artificially synthesized chemical | For agricultural purposes, they are usually used as | Naphthalene Acetic acid, |
| Regulators | compounds, mainly used in agriculture, able to | maturation accelerators, growth stimulators and | Indolbutyric acid, Ethephon, |
| | promote the development and productivity of crops. | inhibitors, flowering, among others. | Chlormequat chloride. |

Table 1. Principal difference among plant growth regulators and phytohormones.

4. Phytohormones

Unlike hormones of animals, in plants there are no specialized sites or organs for biosynthesis of phytohormones, therefore, these can be generated anywhere. It is now known that plant development is regulated by the following groups of phytohormones: AUXs, GBRs, CTKs. ETH. and ABSAc usually referred as the classical phytohormones (Davies, 2010). In addition, other signaling molecules with similar activities to plant phytohormones have been identified that play an important role in disease resistance and defense against herbivores such as brassinosteroids (BRSTs), jasmonic acid (JMAc), salicylic acid (SLAc), strigolactones (STGLs), systemin peptides, and nitric oxide (NO) (Smith et al., 2017). Even though NO is considered an important signaling molecule, and intermediary in metabolic processes by many scientists, is still not recognized as a phytohormone simply because it is an inorganic compound (Arc et al., 2013). Nevertheless, the number of phytohormones and messenger agents within plants will surely continue increasing as knowledge expands and researchers can build consensus on new evidence and understanding of the chemical reactions occurring within plants.

Almost all phytohormones have been found in sieve elements and it is believed that this is where long-distance transport occurs. Besides, transport between different plant organs is important because these chemical messengers can signal to one organ the status of the other, generally by pathways based on transportation through phloem and xylem; for example, buds produce growth regulators such as AUXs, which can be rapidly transported to the roots via the phloem, whereas roots produce CTKs, which are translocated to the buds via the xylem. Another form of transport of various hormones, which are weak acids, is the diffusion of them across cell membranes when they are in their protonated form (Vanneste and Friml, 2009).

In order to expand the information relevant to each of the plant hormones discovered so far, in the following sections each of the biosynthetic pathways and their main applications are presented consecutively.

4.1. Auxins (AUXs)

In 1881, Charles Darwin and his son published the book "The Power of Movement in Plants", where they studied the phenomenon of phototropism in plants (Darwin, 1880). In 1926, Frits Went continued with the study growth stimulus, evidencing the presence of a growth-promoting chemical compound that accumulated on the side opposite the illuminated zone, being the first AUX identified (Thimann, 1940). Indole-3-acetic acid (IAA) was considered as the most important AUX due to its plant-growth regulating potential and physiological relevance, being initially isolated from human urine (Kögl et al., 1934) and interestingly not from plants; many other compounds have been used as auxins including indole-3butyric acid (IBA), indole-3-propionic acid (IPrA), and naphthalene acetic acid (NAA), among others (Enders and Strader, 2015) (see Figure 2).



Figure 2. Some natural and synthetic auxins.

MT-Pallantia Publisher

Generally, definition AUX includes all natural and synthetically originated chemicals that stimulate the elongation of structures initially emerging from the seed (coleoptile), the stretching of stem sections, the formation of adventitious roots in leaves and stems, cell division and other development phenomena associated with cell elongation and with biological activities similar to those caused by IAA (Enders and Strader, 2015). Hence, the term AUX is currently available as a physiological definition describing a set of substances in terms of functionality for plants, consequently, a single molecular structure cannot be used to the chemical description of these substances (Ferro et al., 2007). Note that, whereas IAA and IBA correspond to a heterocyclic structure characterized by an indole ring with one N-alkyl carboxylic acid group on position 3,

phenylacetic acid (PAA) and napthaleneacetic acid (NAA) contain the N-alkyl carboxylic acid group on phenyl and naphthyl rings, respectively (see Figure 2).

4.1.1 Biosynthesis of AUXs

Since auxins are a set of chemical substances of a different nature, their biosynthesis cannot be determined by a single route. However, given the presence of the indole ring in the structure of several of these biomolecules, e.g., IAA, 4-Cl-IAA, IBA and IPrA, it is possible to describe a biosynthetic pathway for groups of molecules with similar structures, however, besides of structural criteria, biosynthetic routes depend on type of plant.



Figure 3. Various pathways for biosynthesis of IAA in plants and bacteria. The enzymes correspond: tryptophan synthases (TSB1 and TSB2), tryptophan N-monooxygenases (CYP79B2/CYP79B2), a family of tryptophan-aminotransferases (TAA and TAT), amidase (AMI1), a class of plant flavin monooxygenase (YUCCA) and nitrilase isoenzymes (NIT1/NIT2/NIT3).



For example, depending of plant species, IAA biosynthesis can occur via several biosynthetic routes, however, the most important is the tryptophan-dependent route where the indole-3-pyruvic acid (IPA) is an intermediary. Thus, this pathway involves the biosynthesis of tryptophan, followed of deamination reaction of amino acid to form one α -ketoacids (i.e., IPA); later, by decarboxylation indole-3-acetaldehyde (IAld) and Indole-3acetaldehyde are formed. Finally, these are oxidized to IAA by enzymatic transformation mediated by specific dehydrogenases. Other biosynthetic pathways occur similarly to the IPA pathway, except that the order of the deamination and decarboxylation reactions and enzymes implied in the biosynthesis are different. Although free IAA is the biologically active form of the hormone, the vast majority of AUXs in plants are in a covalently bound state. These conjugated or "bound" auxins have been identified in higher plants and are considered hormonally inactive. On the other hand, as it is shown in Figure 3, also it is possible the biosynthesis by a tryptophane-independent route. In this case, indole-3-acetaldehyde is formed as intermediary, which is oxidized to form IAA (Zhao, 2012; Korasick et al., 2013).

As additional comment, it is interesting highlight that, although AUXs are chemically diverse, different compounds have been synthesized and tested to mimic their bioactivity or modifier it. For example, it has been evidenced that 4-Cl-IAA (synthetic molecule) is much more active auxin than IAA (biomolecule) being explained this effect due to that IAA is more rapidly metabolized than 4-Cl-IAA (Karcz, 2002).

4.1.2 Applications of auxins

Evidently, the first application of AUXs is to promote the plant growth by increasing the number of cells in buds. The main factor controlling this growth is their distribution, being essential for the early rooting of stems and probably for the formation of new adventitious roots. Thus, it can be affirmed that AUXs can be used in agricultural application to promote the cell division in the meristem and other plant tissues, stimulate the wound exudation in plant tissue, inhibit the development of lateral shoots and impede the root elongation (Ivanchenko et al., 2010; Overvoorde et al., 2010). In general terms, the use of AUXs can increase crop productivity through different results such as variation in flowering, seed production, biomass production, inhibition of shoots, roots or other plant tissue. The exact concentration at which growth is reduced or inhibited varies with each plant species and the type of AUX used. But also, the growth inhibition of each AUX is at the limits of toxicity and sometimes the inhibition observed can be totally to expected depending on the state, form and site of application to the plant (Thimann, 1939).

The natural AUX, IAA, used in tissue culture for plant propagation, are also used to stimulate rapid rooting in cuttings of a wide range of trees and shrubs, annual and perennial; e.g., IBA, see Figure 2. Using IBA and NAA simultaneously at higher doses allows for flowering or fruit thinning in apples and pears. Using lower doses of these AUXs together with 2,4D (synthetic AUX) could improve pre-harvest fruit retention. Carbaryl can be used to improve fruit

color and, alike to 2,4-dichlorophenosyacetic acid or 2,4-D, it is a synthetic AUX. Additionally, 2,4-D is one of AUX most widely used as selective herbicides in the world (Woodward and Bartel, 2005; Castro et al., 2017).

On the other hand, in medicine, PAA is an agent used as adjunct to treat acute hyperammonemia that is a health affectation characterized because the patient shows elevated levels of plasma ammonia (DB09269), in chemical industry has been proposed as precursors of phenolic compounds esters to produce biogas and biodiesel (Zieniuk et al., 2020), and in the food industry as antioxidant due to its high bioavailability and good water solubility (Chen et al., 2020). But also, in medicine, derivate of IAA, i.e., hydroxy-IAA, is a biomarker for midgut carcinoid tumors which can also be useful in characterizing a variety of diseases and disorders (Feelders et al., 2012), including those diseases associated with changes in the levels of 5-5-hydroxytryptamine or serotonin (Ewang-Emukowhate et al., 2019). In addition, it is used as a molecular template for the synthesis of molecularly imprinted polymers in the analysis of auxin traces in plant tissues (Kugimiya and Takeuchi, 1999; Zhang et al., 2010).

4.2. Gibberellins (GBRs)

GBRs are endogenous plant growth regulators, including tetracyclic and diterpenoid compounds. Most GBRs are biologically inactive, being mainly intermediates and precursors in the biosynthesis or degradation of bioactive GBRs (Salazar-Cerezo et al., 2018). GBRs are usually known as gibberellic acids, they were discovered in the 1930s in Japan associated to fungal disease in rice crops called "foolish seedling" disease or "bakanae", which is characterized because plants to grow inordinately long and seed production are discarded. This rice disease is induced by the presence of a chemical compound secreted by the phytopathogenic fungus *Gibberella fujikuroi*, thus receiving the name of Giberellin A.

In later years, 3 different gibberellins were separated and characterized from Gibberellin A, respectively named gibberellins (GA1, GA2 and GA3) (Gupta and Chakrabarty, 2013). Structurally, GBR is a class of diterpenoid, with four isoprene units, forming the kaurene cycle. So far 136 GBRs have been identified in higher plants, fungi and bacteria, of which only a few are bioactive (see Figure 4).

In addition, genetic tests have shown GA3 is the most active GBR being frequently produced at industrial level for agronomic and horticultural purposes (Cowling et al., 1998; MacMillan, 2001). In contrast, the most notable discovery of GBR activity was in the use of semi-dwarf mutant varieties of rice and wheat, which have a gene that modifies GBR biosynthesis, without impeding other processes of plant development and greatly improving grain productivity in the absence of GBR (Spielmeyer et al., 2002). GBRs metabolism is regulated by environmental stimuli, such as light, temperature, water and nutrient status, as well as by abiotic and biotic stresses, which can lead to an increase or decrease in GBRs content (Toyomasu et al., 1998).

Biosynthesis of GBRs (see Figure 5) and their applications are shown below.







GA6

GA7





Figure 5. Scheme of GBR biosynthesis pathway.

4.2.1 Biosynthesis of Gibberellin

The GBR biosynthesis pathway has been established through extensive biochemical and genetic studies in higher plants, fungi and bacteria (Salazar-Cerezo et al., 2018). In general, GBRs are synthesized by the action of several enzymes including terpene

cyclases, cytochrome P450 mono-oxygenases and 2-oxoglutaratedependent dioxygenases, which are located in the plastids, at the endomembrane system and cytosol, respectively.

GAs-Bioactive

The biochemical pathway for the synthesis of GBRs starts from geranylgeranyl diphosphate (GGPP) (see Figure 5) via isopentenyl diphosphate, which is the 5-carbon building block for all



terpenoid/isoprenoid compounds, initially a series of enzymes, such as ent-copalyl diphosphate synthase (CPS) and ent-kaurene synthase (KS) convert GGPP to ent-kaurene, ent-kaurene oxidase (eKO) and ent-kaurenoic acid oxidase (KAO) convert ent-kaurene to GA12, and GA20-oxidase (GA20ox) and GA3-oxidase (GA3ox) catalyze the conversion of GA12 to bioactive-GAs (GA1 or GA4) (Jiang and Asami, 2018; Salazar-Cerezo et al., 2018). In brief:

GGPP | CPS + KS \rightarrow ent-kaurene ent-kaurene | eKO + KAO \rightarrow GA12 GA12 | GA20ox + GA3ox \rightarrow bioactive-GAs (GA1 or GA4)

where vertical bar means "in the presence of".

4.2.2 Applications of Gibberellins

GBRs are used in agriculture to regulate many aspects of plant growth and development. The main applications include cell division and elongation, seed germination, stem and hypocotyl elongation, root growth, flower induction, dormancy regulation, control adaptation to biotic and abiotic stresses (Gao et al., 2017). The use of GBRs is strongly related to environmental conditions and plant type. Thus, the circadian clock directly influences GBR biosynthesis and signaling, thus photoperiodic control of stem elongation in some plants under long-day conditions is mediated by GBRs; for example, application of GBR to rosette plants under short-day conditions promotes stem growth, while treatment with GBR-biosynthesis inhibitors suppresses stem elongation under long-day conditions (Xu et al., 1997).

Endogenous GBR levels are also regulated by abiotic stress, temperature variation, salt concentration and osmotic stress through GBR biosynthesis or deactivation pathway enzymes. For example, reduced GBR levels and signaling have been shown to contribute with the growth retardation in plants when these are exposed to various stresses, including cold, salt and osmotic stress (Colebrook et al., 2014). Otherwise, GBR plays an important role in fruit ripening. In particular, when they are combined with another type of phytohormone, ripening processes of some fruits can be controlled, e.g., for example, GBR are essential for development, the shape and ripening of tomato fruit (Li et al., 2019). Another advantage of using GBRs is related to germination; for example, endogenous growth regulating hormones (e.g., GBR and ABA) in conjunction with environmental factors (e.g., light, temperature and humidity) control the seed dormancy until germination (Gupta and Chakrabarty, 2013). GBRs can stimulate seed germination, while ABA is involved in the establishment and maintenance of dormancy. In this way, during seed germination embryonic GBR is released which triggers seed coat weakness by stimulating the expression of genes involved in cell expansion and modification (Finkelstein et al., 2008).

On the other hand, non-agriculture applications of GBRs are rare. These are practically non-existent. The reason for the above may be the screening of potential uses as a result of its strong use and applications in agriculture. Furthermore, from a synthetic point of view GBRs are complex structures whose main industrial strategy is biotechnological. Regardless of the above, some exploratory studies have been performed with gibberellin acid (GAc). GAc has been shown to have a positive influence on body weight, food conversion rate, and fertility. In addition, in experiments carried out in mice, subjected to a GA3 diet, it was shown that this substance can have strong effects in animals. Among the effects identified is the doubling of the rodent population through an increase in the fertility of individuals (Hosseinch et al., 2013). Consequently, it has been suggested that GBRs have an effect on the endocrine system of mammals, therefore, it can be used for the treatment of fertility disorders, but also for animal production (growth acceleration) (Csaba et al., 1977; Hosseinch et al., 2013). From the results obtained in male chicks, it was shown that GA3 stimulates the growth of the ridges (Gawienowski et al., 1977; Hosseinch et al., 2013). From the above, an enormous potential is inferred in the bioproduction of chemicals. For example, the crest of chicks is rich in Hyaluronic Acid which is used in biomedical and industrial applications (Kogan et al., 2007). However, it is important to indicate that chronic GA3 consumption increased tumor formation and oxidative stress, and morphological changes in sperm (Erin et al., 2008). GBRs are considered to be relatively harmless for animals and human. However, as it was previously mentioned, GBRs have adverse effects on various animal tissues. In this way, prolonged exposition to residues of GA3 in diet originated from consumption of different types of fruits and vegetables treated with GA3, or by exposure to residues of GA3 in drinking water could negatively impact in human health (Hosseinch et al., 2013). I this point, are the GBRs emergent pollutants? From a conceptual point of view the response is affirmative, however, to date there is no information supporting this claim.

4.3. Cytokinins (CTKs)

In the 1950s Skoog and co-workers discovered a new phytohormone able to promote growth, cell division and differentiation; which were named CTKs, which affect the main characteristics of the leaves, through cell expansion, improving photosynthesis by promoting chloroplast differentiation and stomatal opening, delaying regular senescence, improving the ability of organs and tissues to absorb various nutrients, activating the formation of pigments in the cells and stimulating the formation of new shoots. In addition, CTKs regulate the responses during the uptake of essential elements from the soil (e.g., N, P, S, Fe, etc.), the formation of the vascular system, nitrogen-fixing nodules in plant roots, and the development of the female gametophyte. These phytohormones play an important role in the defense of plants against abiotic environmental stressors such as cold, drought, heat, and soil salinity, and biotic stressors as viruses, bacteria, and fungi (Durmus and Kadioğlu, 2005). The hormonal activity of CTKs depend on their structure trans-Zeatin (see Figure 6 (1)). This is the best known natural CTKs and exhibiting a high affinity for all tested CTK receptor isoforms or "protein variant".

The cis-Zeatin shows a much lower cytokinin activity compared to the trans-isomer (see Figure 6 (2)). In general, natural CTKs act in plants at very low concentrations, mainly at the nanomolar level (1-



50 pmol g⁻¹) and at higher concentrations the effects can be reversed (Oshchepkov et al., 2020). Furthermore, CTKs are not only restricted to higher plants, since they can be found in lower order plants, such as algae, bacteria, insect parasites and nematodes, as well as in some physical components of the environment, e.g., soil and water (Stirk and van Staden, 2010).

4.3.1 Biosynthesis of Cytokinins

Natural CTKs are adenine derivatives with a variable side chain at the 6-position of purine, the isoprenoid chain, their derivatives and an aromatic ring (single or modified) can be substituted by an exocyclic nitrogen atom (see Figure 6). Glycosidic conjugates play a role in cytokinin transport, protection against degradation and reversible and irreversible inactivation (Werner et al., 2001), and can have a urea-based synthetic origin. Roots are among the most important sites of CTKs biosynthesis in angiosperms; therefore, they have high concentrations of endogenous CTKs. In addition, the movement of CTKs between soil and roots sometimes affects their synthesis and metabolism in the root and plant. There is evidence of exogenous CTK uptake through the root can influence the plant metabolism (Stirk and van Staden, 2010). CTK biosynthesis is regulated by three key enzymes (see Figure 7). First, adenosine phosphate isopentenyltransferase (IPT), which catalyzes the formation of isopentenyladenine (iP) nucleotides, specifically, iP riboside 5'-diphosphate (iPRDP) and iP riboside 5'-triphosphate (iPRTP), from dimethyl diphosphate (DMAPP) and adenine nucleotides, with preferential use of ATP or ADP (Jiang and Asami, 2018); cytochrome P450 monooxygenase 735A (CYP735A) which acts on the prenyl side chain end of iP ribonucleotides, catalyzing iP nucleotides to trans-Zeatin (tZ) nucleotides, and Lonely-Guy phosphoribohydrolase (LOG) which converts inactive tZ nucleotides to active tZ (Osugi and Sakakibara, 2015).

4.3.2 Applications of Cytokinins

CTKs has a positive effect on top growth of plants by stimulating of apical activity and lateral meristems. Conversely, when their content is reduced, it decreases the chlorophyll content of plants affecting the photosynthetic activity. In the agricultural practice, especially in fruit crops, vegetables and ornamental species, the application of exogenous CTKs, both natural and synthetic, is used to accelerate growth, stimulate germination, lateral branching and shoot breakage, and improve yield (Werner et al., 2001). In evaluations using CTKs in cereal crops, an increasing on grain yield were achieved, particularly under stress conditions in vegetables. In fruit trees, fruit size and weight were increased by the application of CTKs. In cotton crops, yield improved and increased drought resistance (Stirk and van Staden, 2010; Oshchepkov et al., 2020). In addition, the exogenous use of CTKs in crops has been shown to reduce the toxicity of the herbicide paraquat in some maize varieties, resulting in an increase in the activity of antioxidant enzymes (Durmuş and Kadioğlu, 2005).

An important role of CTKs is to regulate plant immunity during host-pathogen interactions. In this way, the treatment of plants with exogenous or induced CTKs has evidenced an improvement in resistance of tomato plants against infections with many different types of pathogens (Gupta et al., 2020).

CTKs are essential components of plant tissue culture media in biotechnological procedures of micropropagation and transgenic plant production (Villanueva et al., 2013). Efficient in vitro shoot regeneration and micropropagation methods use CTKs in different concentrations for many crops including flower, potato, sugar cane, banana, apple, strawberry and many medicinal and ornamental plants (Chamorro et al., 2007; Villanueva et al. 2013; Oshchepkov et al., 2020).



Figure 6. Common natural and synthetic CTKs derived from adenine and based on urea.



Figure 7. Scheme of CTK biosynthesis pathway.

Moreover, CTKs have shown medicinal potential. For example, trans-Zeatin riboside has exhibited more or less efficient cytotoxicity against a wide range malignant cells: glioblastoma, rhabdomyosarcoma, breast cancer, central nervous system (CNS) tumors, colorectal cancer, lung cancer, leukemia, melanoma, prostate, ovarian and kidney cancer (Voller et al., 2019). CTKs (6-benzylaminopurine and kinetin) in vitro have shown antioxidant activity of fibroblast cells, which can be used in the prevention and treatment of many skin diseases associated with oxidative stress, such as psoriasis and granuloma annulare (Jabłońska-Trypuć et al., 2016). CTKs and their ribosides exhibit neuroprotective activity, trans-Zeatin (1) has a broad spectrum of activity in the treatment of

central nervous system diseases, in particular Alzheimer's disease (Heo et al., 2002). Other reported potential uses of CTKs for medicinal benefit include anti-inflammatory activity, inhibitor of Helicobacter pylori, antiviral activity, plasmodium inhibitor, among others (Oshchepkov et al., 2020).

4.4. Ethylene (ETH)

ETH is a low molecular weight unsaturated hydrocarbon $(CH_2=CH_2, 28 \text{ g/mol})$ able to regulate plant growth and senescence, and it plays an important role in the different processes during the ripening of agricultural products. ETH is found in all plants in



nature, its contents depend on environment and the developmental stage of the plant, varying at least 100-fold during the life cycle. ETH is one of the first chemicals identified as a natural growth regulator and influencer of plant development. Its history dates back to the early 19th century, being the Russian student Neljubov the first to describe the threefold growth response pea seedlings by using of ETH: (1) reduced stature, (2) exaggerated hypocotyl hook and (3) inhibition of root growth. Though ETH was the first phytohormone chemically identified, it was only until the second half of the 20th century, with the advent of gas chromatography, that ETH achieved respectability as an endogenous regulatory hormone for plant growth and development. As a gas, ETH diffuses rapidly from production sites hindering its detection (Grierson, 2012; Jiang and Asami, 2018). A particularity of ETH is its ability to interact with other phytohormones at the molecular level. For example, ETH interact with AUXs and ABSAc to promote the leaf growth. This interaction is described as an effect of AUX and ABSAc on ETH production; but also, CTKs play an important role in leaf initiation through the maintenance of S-adenosyl-methionine (SAM), that is an immediate metabolite for ETH biosynthesis (Iqbal et al., 2017).

4.4.1 Biosynthesis of Ethylene

There are three pathways involved in ethylene production: (i) the activated methyl cycle, (ii) the S-methylmethionine cycle, and (iii) the methionine or Yang cycle. Generally, ETH is synthesized by a relatively simple conversion using three enzymatic reactions, firstly, SAM is synthesized from the processing of methionine by SAM synthetase. Later, 1-aminocyclopropane-1-carboxylic acid (ACC) is generated by enzymatic action of ACC synthase (ACS) and, finally, ACC is oxidized to ETH by ACC oxidase (ACO) (see Figure 8). Simultaneously, cyanide is removed by cyanoalanine synthase and release of water takes place (Pattyn et al., 2021). ETH is accumulated in large concentrations in poorly ventilated places, in plants, it is used for defense against pathogens (mainly necrotrophs), but also, during nodulation in the symbiosis for nitrogen fixation, for cell elongation, and as a mechanism for survival in periods of flooding; additionally, the plant can use it in the regulation of fruit ripening, flowering and senescence. ETH also affects various aspects of root architecture, including primary elongation, lateral

development, shape and modulates differential root growth (Vandenbussche and Van Der Straeten, 2012).

4.4.2 Overview applications of Ethylene

In agriculture, useful of ETH is limited, mainly in open field crops, because it is a gas and therefore has a high diffusivity dependent on temperature and concentration. ETH is involved in promoting senescence, abscission and ripening of horticultural products, so by reducing its biosynthesis it is possible to slow down the postharvest deterioration of fruits and vegetables, thus extending shelf life and limiting postharvest losses. However, in food industry its use is more extended. In the production of fruits, the ripening control is an important factor. Thus, in climacteric fruits, i.e., those that can mature separately from the plant, such as apple, banana, mango, papaya, pear, apricot, peach, plum, avocado, plantain, guava, nectarine, passion fruit, blueberry, cantaloupe among other, ETH has been identified to produce an effect on ripening (Chen et al., 2018). Thus, ETH becomes the main signaling molecule controlling most aspects of climacteric fruit ripening. In these fruits, ETH is autocatalytically generated during their ripening by activating the gene modifying enzyme ACC with the subsequent increasing on ETH generation. In contrast, in non-climacteric fruits, ETH does not produce autocatalytic ETH, and therefore, ETH is not the trigger for the ripening process (Barry and Giovannoni, 2007).

4.5. Abscisic acid (ABSAc)

ABSAc is a signaling molecule regulating many aspects of plant growth including embryo maturation, seed dormancy, germination, cell division and elongation, and flower induction, but also, it regulates response to environmental stresses produced by drought, salinity, cold, pathogen attack and UV radiation. It was first isolated and identified in the early 1960s from young cotton fruit during studies related with the identification of compounds responsible for fruit abscission, being initially named "abscisine II" (Ohkuma et al., 1963). Structurally, ABSAc is a 15-carbon compound (C15) belonging to terpenoids. In addition, the orientation of the carboxyl group at carbon 2 determines the trans or cis isomers of ABSAc. In addition, a symmetric carbon atom at the 1' position in the ring



Figure 8. Scheme of ETH biosynthesis pathway.



Figure 9. Scheme of ABSAc biosynthesis pathway.

determines the S(+) or R(-) enantiomers.

The natural form is (S)-cis-ABSAc, whereas commercially is available as a mixture of the S and R forms in approximately equal amounts. Light can isomerize (S)-cis-ABSAc and (R)-cis-ABSAc to produce the biologically inactive forms (S)-2-trans-ABSAc and (R)-2-trans-ABSAc, respectively. Both (S)-cis- and (R)-cis- forms have a strong activity on prolonged ABSAc responses, such as seed maturation; however, (S)-cis-ABSAc has stronger activity in rapid ABA responses, such as stomatal closure (Xiong and Zhu, 2003). ABSAc is present in all plants (green algae and terrestrial plants), some phytopathogenic fungi, bacteria and metazoans from sea sponges and humans (Jiang and Asami, 2018).

4.5.1 Biosynthesis of Abscisic acid

There are at least two biosynthetic pathways for ABSAc production: (i) fungi-produced ABSAc obtained directly from farnesyl pyrophosphate, and (ii) in plant-produced synthesis obtained from an "indirect" pathway via cleavage of a β -carotene precursor via xanthoxin and ABSAc-aldehyde (C40 pathway). Conversion stage of biosynthesis is regulated by drought stress (see Figure 9). Genetic evidence supports the C40 pathway, whereas biochemical studies suggest that neoxanthin cleavage is a key regulatory step in ABSAc biosynthesis. First, in the chloroplast, zeaxanthin epoxidase (ZEP) converts zeaxanthin to violaxanthin; later, neoxanthin synthase and a series of structural transformations generate neoxanthin. In the presence of oxygen xanthoxin is synthesized, and finally, cisxanthoxin is converted to ABSAc by sequential reactions catalyzed by xanthoxin dehydrogenase in the cytoplasm (Xiong and Zhu 2003; Finkelstein 2013). Additionally, there are reports on the different mechanisms for the chemical synthesis of ABSAc and its analogues (Bassaganya-Riera et al., 2010).

4.5.2 Overview applications of Abscisic acid

ABSAc regulates drought stress responses by mediating stomatal closure producing a reducing of water loss by transpiration. Exogenous applications of ABSAc delay wilting and allow plants to survive short periods of severe drought (Li et al., 2011; Sakthivel et al., 2016; Magnone et al., 2020). ABSAc plays a key role in the induction and maintenance of seed dormancy, it can inhibit the transition from embryonic to germination growth, alter root architecture and change the pattern of growth and quiescence in plant roots. Similarly, ABSAc is an important mediator of drought, salt and osmotic stress. Exogenous application of ABSAc to plants can enhance their adaptive responses to stress by increasing tolerance in some plant species (Sah et al., 2016).

On the other hand, other applications of ABSAc have been evaluated. For example, ABSAc has been suggested as a drug candidate in humans for a number of clinically relevant human diseases, e.g., diabetes; however, these applications are in exploration and development stages (Li et al., 2011; Sakthivel et al., 2016). Studies using mice as animal model have shown antiinflammatory and anti-diabetic effects, inflammatory bowel disease, atherosclerosis, and influenza infection (Magnone et al., 2020). In the field of functional foods, especially nutraceuticals, ABSAc is a candidate for glucose control by its use alike to additive. This application is suggested due to role of ABSAc in mammals where physiological response to glucose intake, a role until then shared by insulin and by the incretin glucagon-like peptide-1 (GLP-



1), is observed also for ABSAc (Bassaganya-Riera et al., 2010; Zocchi et al., 2017).

4.6. Brassinosteroids (BRSTs)

BRSTs comprise a class of at least 70 polyhydroxylated sterol derivatives biosynthesized by plants. These compounds are structurally alike to animal steroid hormones which regulate the expression of numerous genes, influence the activity of complex metabolic pathways, contribute to the regulation of cell division and differentiation, help to control to morphogenesis, and regulate specific processes of plant growth such as flowering and cell expansion (Clouse, 2011). Their discovery dates back to the analysis of organic pollen extracts from numerous species in the 1970s, when Mitchell and his colleagues at the USDA isolated an active extract from pollen of Brassica napus (canola) (Mitchell et al., 1970). Initially they were named as "Brassins". BRSTs have a pronounced effect on elongation and their exogenous use can increase the production of young seedlings in some leafy vegetables and potatoes (Clouse, 2011). The BRSTs family consists of Brassinolide (BL), 68 others free BRSTs and several conjugates. A BL is a polyhydroxylated derivative of 5a-cholestan, namely 2a, 3a, 22, 23tetrahydroxy-24-methyl- B-homo-7-oxa-5a-cholestan-6-one (see Figure 10). BRSTs differ from BL by variations at C-2 and C-3 of the A-ring, the presence of a lactone, ketone or deoxo function at C-

6 of the B-ring, the stereochemistry of the side-chain hydroxyl groups, and the presence or absence of a methyl (or methylene) or ethyl (or ethylene) groups at C-24 (Peres et al., 2019).

On the other hand, conjugates are glycosylated, meristylated and laurylated derivatives from A-ring or side-chain hydroxyls. The optimal structure of BRSTs for a higher activity is usually those found in BL, which consists of a lactone function at C-6/C-7, cisvicinal hydroxyls at C-2 and C-3, R-configuration of the hydroxyls at C-22/C-23 and a methyl substitution at C-24 (Clouse, 2011). Endogenous levels of BRSTs vary according to plant organ type, tissue age and species, but also, among pollen and immature seeds containing the highest levels on the order of nanogram/gram.

4.6.1 Biosynthesis of Brassinoesteroids

Biosynthesis of BRSTs is a complex and multi-step process occurring in the endoplasmic reticulum. From stereochemistry it has been predicted that the plant sterol (i.e., campesterol) is converted to BL via teasterone, typhasterol and castasterone. In addition, it has been shown that campesterol is the progenitor of BL and is very likely to BRSTs derived from common plant sterols with side-chain structure. Generally speaking, plant sterols are biosynthesized via the isoprenoid pathway through acetyl-CoA, mevalonate, isopentenyl pyrophosphate, geranyl pyrophosphate and farnesyl pyrophosphate (see Figure 10).







Coenzyme A (CoA) is a key metabolite, in isoprenoid biosynthesis. The initial step is the condensation of acetate into squalene via the formation of mevalonate, a C5 isoprene, and a series of intermediate reactions and mediated by 3-hydroxy-3-methyl-glutaryl-CoA reductase (HMCGR). Afterward, a series of cyclisation reactions of 2,3-squalene occur until the formation of cycloartenol, which are mediated by cycloartenol synthase (CAS 1) and numerous other specialized oxidosqualene cyclases (OSCs) (Valitova et al., 2016). The next step consists in an extensive series of reactions to transform cycloartenol to campesterol, the conversion of cycloartenol to campesterol starts with C-24 alkylation of the side chain; process being catalyzed by the enzymes sterol methyl transferase 1 (SMT1) and sterol reductases (DWFs) (Peres et al., 2019). Finally, it is important to highlight that plant sterols are precursors of BRSTs, being, in all plants, ß-sitosterol, campesterol, and stigmasterol the predominant sterols, which differ and vary in their contents depending on the plant species.

4.6.2 Applications of Brassinosteroids

The first application of BRSTs is in agriculture. Thus, BRSTs mediate in plants under abiotic and biotic stress, including salt and

drought stress, temperature extremes and pathogen attack. They can be used to control the timing of flowering of some plant species by exogenous application. Plants deficient in BRSTs have been found to exhibit dwarfing phenotypes, short petioles, delayed flowering and reduced fertility (Zullo and Adam, 2002; Peres et al., 2019). BRSTs have demonstrated to be useful in the increasing of the yields of seed and leaf of some legume, cereal and vegetable crops. For agricultural purposes, BRSTs can be applied by spraying, spreading, coating or dipping of plants or their organs or soil. The amount to be applied varies depending on the structure of the BRSTs, the formulation used, the type of plant to be treated and the desired effect. Generally, the concentration in the preparation ranges from 0.01 to 100 ppm, and can be applied with other agrochemicals, such as other plant hormones or growth regulators, fertilizers, herbicides, insecticides and other adjuvants (Zullo and Adam, 2002). Due to their similarity to animal steroids, recent studies mention the potential use of BRSTs for biomedical applications (see Table 2). Thus, some applications are directed towards the drug development and treatments against cancer, virus, fungal, and bacterial. Anticholesteromics and anti-inflammatory bioactivities of BRSTs in animal models also have been evidenced (Kohli et al., 2020).

Table 2. Potential applications of BRSTs in medicine from different animal models (adapted from Kohli et al., 2020).

| Compounds | Potential effect | Mechanism of action |
|--|--|---|
| Brassinolide | Increased resistance of Nicotiana benthamiana against Tobacco mosaic virus (TMV). | BES1/BZR1 suppressed RBOHB-dependent reactive oxygen species (ROS) regulated by MEK2-SIPK signaling network. |
| (22S,23S)-3β-bromo-5α,22,23- trihydroxystigmastan-6-one (22S,23S)-3β-bromo-5α,22,23- trihydroxystigmastan-6-one | Antiviral activity against Junin virus (RNA causing Argentine hemorrhagic fever). Hampering the herpes simplex virus (HSV) type 1. | Deterioration of RNA replication of trihydroxystigmastan-6-one resulting in formation of viral glycoproteins. Inhibition of the expression of HSV antigen and reduced the production of HSV late protein. Altering of replication in Vero cells by affecting the later stages of virus multiplication. |
| 28-HomoCS and 24-EpiBL | Antiproliferative activity, pro-apoptotic activity, and cell growth inhibitory responses in several human cell lines without effect on non-tumor cell growth | Cell blockade and apoptosis of both hormone-sensitive and insensitive human breast cancer. |
| 24-EpiBL and 24-EpiCS | Antiproliferative, anticancer, antiangiogenic, antiviral, and antibacterial properties in the animal system | Inhibit replication of viruses in confluent with human cell culture, including cytotoxic effects in various types of cancer cells but normal human cells. |
| 28-HomoCS | Antiviral effect against RNA and DNA viruses | Limiting virus protein synthesis and mature viral particle formation. |
| (22S,23S)-22,23- dihydroxystigmast-4-en-3-one and (22S,23S)-22,23- dihydroxystigmasta-1,4-dien-3- one | Immuno-modulatory and neuro-protective activity | Blocked HSV-1 induced activation of NF α B by inhibiting its translocation to the nucleus of infected conneal and conjunctival cells in vitro, as well as significantly reduced the secretion of TNF- α infected NHC cells. |
| 28-HomoBL and 24-EpiBL | Anticancer bioactivities in various cell lines i.e., CEM (T- Lymophoblastic Leukemia), A549 (lung carcinoma), MCF-7 (breast carcinoma). LNCaP (prostate cancer) among others. | All these cells were found non-viable in response to 4-fold dilution for 72 h of IC50 value of BRs observed from Calcein AM assav. |
| 24-EpiBL | In vitro antiproliferative effect in the animal cell lines | Cytotoxicity in PC-3 cells activating polyamines catabolic machinery in prostate cancer cells |
| | Mitochondria-regulated cell death in colon cancer cells | Upregulation of Foxo3a and protein tryokinase Src p38, after the activation of P13K/AKT. |
| | Amelioration of Turnip crinkle virus infection in Arabidopsis thaliana, BAK1 or BKK1 are essential components 24-EpiBL minimized fungal initiated ROS and increased resistance towards Fusarium | Increase in activity of antioxidant enzymes and subsequent gene expression and also lowered photosystem deterioration Reduced Fusarium wilt in cucumber and enhanced their antioxidant and phenolic levels in roots. |



4.7. Jasmonic acid (JMAc)

JMAc, or 3-oxo-2-2'-cis-pentenyl-cyclopentane-1-acetic acid, is an endogenous lipidic phytohormone, which plays an important role in the response against biotic and abiotic stress by inducing the expression of characteristic genes (examples are shown in the Table 3, a detail description is given by (Wang et al., 2020), as well as in the growth and development of higher plants. JMAc, its methyl ester (MeJA), and isoleucine conjugate of JMAc (JA-Ile) are derivatives of fatty acids collectively known as jasmonates. JMAc can induce stomatal opening, inhibit Rubisco biosynthesis and affect the nitrogen and phosphorus uptake, and the transportation of organic compounds, such as glucose. JMAc have been identified in 206 plant species belonging to 150 genera, including algae, mosses, and fungi (Babenko 2015; Ruan et al., 2019). JMAc levels found in plants typically range from 10 to 100 ng/g fresh weight depending on the species, plant organs, and biotic or abiotic stressor (Ghasemi et al., 2014).

4.7.1 Biosynthesis of Jasmonic acid

For biosynthesis of JMAc as precursors are used polyunsaturated fatty acids (PUFA), which are released from chloroplast membranes by the action of lipid hydrolyzing enzymes. This route is called lipoxygenase (LOX) pathway which presents seven enzymatic ways or sub-routes. However, only the sub-route of allene oxide synthase

Table 3. Example of response produced by JSAc on abiotic stress (Wang et al., 2020).

| Stressor | Stressor effect | JMAc effect |
|-------------|---|--|
| Cold | Stress produced by low temperature is a limiting factor for plant growth and development, with a strong influence on the geographical distribution of plants. | Low temperature conditions can induce the expression of JSAc biosynthesis genes, including allene oxide cyclase (AOC), allene oxide synthase1 (AOS1), and lipoxygenase-2 (LOX2). Exogenous JSAc treatment can reduce lipoxygenase activity and increase antioxidant synthesis to enhance cold tolerance in plants. |
| Drought | The impact of drought stress on crops is one of the major reasons for reduction in crop yield reduction and even crop failure. At present, it is increased by the climate change. | In some species, JSAc can minimize water loss by regulating stomatal opening and closing. The concentrations of endogenous JAs increase rapidly following drought stress, and then return to the baseline levels if stress periods are prolonged. Researches evidence that both endogenous and exogenous JSAc participate in drought stress tolerance in plants (e.g., foliar application of MeJA on soybean leaves enhances tolerance capacity to drought stress, and in addition, analysis showed increased levels of sugars phenolic. |
| Salinity | Salt stress interferes with plant metabolism, leading to oxidative stress, malnutrition, membrane disorders, and genotoxicity. | Both endogenous and exogenous JSAc can enhance plant salt stress tolerance. A reduction of salt-induced damage to various plants via increased photosynthetic rates, proline contents, ABA levels have been reported. |
| Heavy metal | Pollution by heavy metals is an environmental problem which can affect the plant growth and development (e.g., decrease of photosynthetic pigment concentrations by exposition to high lead, nickel, cadmium, and manganese). Many of these metals have no beneficial functions in plants, and they can produce toxicity to plants even at very low levels. | The results demonstrate that a low concentration of endogenous JSAc could enhance the sensitivity of seedlings to metals as cadmium. On the other hand, it has been evidenced that exogenous application of JSAc regulate plant responses to heavy metal stress by regulating their antioxidant systems. |
| Light | Light is a key regulator of JSAc biosynthesis and signal transduction. | Exogenous pretreatment of JSAc has been identified to reduce the adverse effects of shortwave Ultraviolet B Rays, with wavelenght among 280–315 nm, or UV-B, on photosystem II function. Effect of JSAc induces phenolic compound production via both JSAc-dependent and JSAc-independent pathways, and enhances sensitivity to JSAc, leading to enhanced expression of the wound-response gene, trypsin proteinase inhibitor. |

(AOS) is associated with the biosynthesis of JMAc. Consequently, only 13-hydroperoxide obtained from α -linolenic acid can be utilized by the AOS for JMAc production. Specifically, after liberation of α -linolenic acid, a molecular oxygen is incorporated by a 13-LOX at carbon atom 13 of the substrate, leading to the formation of a fatty acid hydroperoxide (13-HPOT or 13-hydroperoxylinolenic acid) (see Figure 11). This product is converted to 12-oxo-phytodienoic acid (OPDA) by the three enzymes lipoxygenase, allene oxide synthase (AOS) and allene oxide cyclase. OPDA is then reduced to a cyclopentenone ring by an enzyme located in the peroxisome, 12-oxo-phyto-dienoic acid reductase 3 (OPR). Finally, the reaction product undergoes three cycles of β -oxidation in the peroxisome, generating JMAc (Yan et al., 2013; Ruan et al., 2019).

4.7.2 Applications of Jasmonic acid

JMAc and its derivatives are applied in agriculture as biologically active substances regulating the metabolic processes in plants. In agricultural production, mechanical actions produced by various environmental factors (e.g., insects, herbivores, wind among others) stimulate the high concentration of JMAc at the site of damage understood to be a defensive response of the plant. In addition, it allows improving the in vitro rooting phase in micropropagated rootstock shoots in various crops (Ruzić et al., 2015; Ruan et al., 2019).



In some species of plants *Arabidopsis thaliana*, yellow lupine or *Amaranthus caudatus*, an increasing on JMAc concentrations inhibits or delays seed germination, being this effect identified as another function of JSAc in plants. It has been found that exposing to JMAc of some vegetative vegetable plants (e.g., potato, tomato, cucumber and onion) before the first symptoms of insect infestation contributes to a substantial improvement of plant resistance (Babenko, 2015). Some studies have shown that exogenous application of JMAc on plants increases the amounts of natural antimicrobial agents and antioxidants in extracts and essential oils, increasing flavonoid content and antioxidant capacity (Ghasemi et al., 2014).

To date, JMAc and its derivatives have been tested for biotechnological, medical and agricultural purposes as highly technological regulators of metabolic processes, either as standalone biologically active substances or in combination with other compounds. Recently, JMAc and its derivatives have been highlighted as potential drugs and prodrugs for the treatment of human diseases, demonstrating that these compounds do not cause a significant toxicity to mammals. For example, JMAc has shown anticarcinogenic activity due to its ability to generate apoptosis and suppress the cell growth. Additionally, it can increase survival in animals and humans with lymphomas and induce death in human cell lines related to different diseases as leukemia, melanoma, neuroblastoma, and cancers of lung, colon, and prostate (Ghasemi et al., 2014).

On the other hand, antidepressant and anti-aggressive properties of JMAc have been identified from assays in mice. Another potential application of JMAc is its use as anti-inflammatory agent since it has shown a superior effect to that observed on natural anti-inflammatory prostaglandins. Anti-parasitic effects of JMAc on the

human parasites have been observed. In particular against *Plasmodium falciparum* (i.e., an anitrocytic protozoan parasite that causes one the most severe form of malaria) and *Schistosoma mansoni* (i.e., a parasitic worm residing in blood vessels) (FlescherOrit, 2001).

4.8. Salicylic acid (SLAc)

SLAc plays an essential role in the activation and regulation of multiple responses to biotic and abiotic stress. This phytohormone was first isolated in 1928 from willow bark in Munich by Jhon Buchner (Hayat and Ahmad, 2007). SLAc is a plant phenolic compound structurally formed by an aromatic ring with a hydroxyl group or its functional derivatives (see Figure 12). SLAc is an analogue of acetylsalicylic acid (AcSLAc) better known as aspirin, in some plant species it has been found in concentrations ranged among 1 mg/g and 37.19 mg/g depending on the species and tissue tested (Hayat and Ahmad, 2007).

4.8.1 Biosynthesis of Salicylic acid

Two routes for SLAc biosynthesis in plants have been suggested, firstly: (i) decarboxylation of the cinnamic acid side chain occurs to generate benzoic acid, which undergoes hydroxylation at the C-2 position. Thus, benzoic acid 2-hydroxylase (BA2H) catalyzes the biosynthesis of SLAc from benzoic acid. The second route involves hydroxylation of cinnamic acid to o-coumaric acid followed by its decarboxylation to SLAc. The conversion of cinnamic acid to ocoumaric acid has been found to be catalyzed by trans-cinnamate-4-hydroxylase, however, there has been evidenced that it may also be photo-induced in chloroplasts (Hayat and Ahmad, 2007).









4.8.2 Applications of Salicylic acid

Phenolic compounds influence many physiological and biochemical processes such as photosynthesis, ion uptake, membrane permeability, enzyme activities, flowering, heat production, and plant growth and development. In consequence, SLAc and AcSLAc have a natural application field in agriculture. The above includes other phenolic compounds as gentisic acid and other SLAc analogues exogenous compounds able to accelerate the leaf area gain and dry mass production. Plant responses to the use of SLAc vary according to the species evaluated, the mode of application, and the amount of SLAc used. Its effect is associated with the leaf growth, root inhibition, morphological differentiation rate, variation in chlorophyll content, carotenoids and xanthophylls, a greater efficiency of water use, an improved nitrogen uptake by certain species, the inhibition of ethylene generation, modification of the nutritional status of plants, inhibition of the absorption of certain compounds, and regulation of flowering, among others (Hayat and Ahmad. 2007).

On the other hand, SLAc has been identified as part of the defense mechanisms during plant-microorganism interactions, including bacteria-plant, yeasts-plant and virus-plant. SLAc initially is accumulated in the local infected tissue and then it is propagated throughout the plant to induce acquired systemic resistance in the distal non-infected parts of the plant (Maruri-López et al., 2019). Among the possible uses of SLAc analogues and derivatives are their use as flavoring of foods, candies, beverages and pharmaceuticals. Additionally, the use of AcSLAc for medical applications is well known (Ekinci et al., 2011). Other applications of SLAc are based on its ability to inhibit prostaglandin synthases (cyclooxygenases) by decreasing the concentration of hydroperoxides, in very generic terms, it can help reduce pain, inflammation in rheumatic diseases. Several patents about medicinal uses of SLAc and its derivatives are related to their obtaining, preparation and pharmaceutical formulations. Some medical applications are directed to treatment of thrombotic cardiovascular events, myocardial ischemia, ischemic neurological deficits, pain relief, fever, inflammation, and even it has been described for the prevention and treatment of some types of cancer (Ekinci et al., 2011).

4.9. Strigolactones (STGLs)

STGLs are a group of carotenoid-derived plant hormones present in many plant species from mosses to higher plants, they play an important role in the stimulation and branching in parasitic plants, and symbiosis and growth of arbuscular mycorrhizal fungi in soil. Strigol was the first STGLs isolated, in 1966 and from cotton root exudate. Its name was linked to the plant genus Striga, which is a common parasite of this crop. STGLs regulate developmental processes, including induction of secondary growth, acceleration of leaf senescence, stimulation of internode growth and root elongation, inhibition of axillary bud growth, and formation of adventitious and lateral roots (Halouzka et al., 2020).

4.9.1 Biosynthesis of Strigolactones

The carotenoid pathway is the STGL biosynthetic pathway which takes place mainly in the roots, thus, they can be secreted to the rhizosphere or transported to the shoots. The first step starts with the isomerization of all-trans- β -carotene at carbon position 9 to 9-cis- β -carotene (see Figure 13), which is catalyzed by carotenoid isomerase (D27). Subsequently, 9-cis- β -carotene is converted to carlactone by sequential action of carotenoid cleavage dioxygenases (CCDs). CCD7 and CCD8, which perform stereospecific cleavage, add three oxygens and rearrange the 9-cis- β -10'-carotenal backbone. The carlactone structure is similar to that described for the STGLs, consisting of a C19 backbone and a D-ring. Therefore, carlactone is an intermediate in the biosynthesis of other STGLs.

This conversion includes oxidation and dehydrogenation steps, which are mediated by the ultimate enzyme of STGL biosynthesis: monooxygenase MAX1 (Abe et al., 2014; Marzec and Muszynska, 2015; Wang et al., 2017).

4.9.2 Overview applications of Strigolactones

To date, there are few reports on the field-scale application of STGLs, one of the possible causes being the high cost of STGLs synthesis and the limited knowledge about the side effects of degradation by-products and their possible environmental risks as a result of their use. However, it has been presented evidence on the role of STGLs in plant response to osmotic stresses related with drought and salinity. Other reports have demonstrated that STGLs are related to the regulation of plant root development, although





Figure 13. Scheme of STGLs biosynthesis pathway. In figure SL denotes STGL.

their specific effects may vary according to species and evaluation conditions (Aliche et al., 2020). By instance, inhibition of lateral roots by STGLs and under optimal growth conditions have been studied, thus, it has been observed that during nutritional stress they are able to enhance the nutrient uptake. Therefore, one additional potential use of STGLs is their use in nutrient-poor soils and in organic farming to enhance nutrient uptake from root symbiosis with nutrient-fixing microorganisms under conditions of nutritional stress. On the other hand, their potential medical application has been mentioned from new synthesized analogues of STGLs which have been found to be effective against tumors, showing that these phytohormones have a unique mechanism of inhibiting cancer cells by reducing their viability and promoting apoptosis even at micromolar concentrations (Hasan et al., 2018).

4.10. Plant peptide hormones (PPHs)

Unlike conventional phytohormones some of these PPHs have been shown to be distributed among specific plant species. Therefore, the conventional definition of "plant hormone" is not applicable to these peptides; however, the term "plant peptide hormone" or PPHs has recently been adapted to describe this category of compounds, although even exist controversy about this designation. In general, PPH are peptide biomolecules acting as molecular messengers in key processes such as meristem maintenance, organ abscission, cell elongation, cell proliferation and differentiation, gravitropism, defense against biotic aggressors, regulation of cell division, and development of the guidance system. Among these compounds are phytosulphokines (PSK), hydroxyproline-rich systemin, glycopeptide sistemins (HypSys peptides), CLE peptides, the peptide ligand called Tracheary Element Differentiation Inhibitory Factor (TDIF), among many others (Gancheva et al., 2019; Ghorbani et al., 2014).

Depending on their structural characteristics, signaling peptides can be divided into two distinct groups depending of cysteine content: (i) Group I consisting of cysteine-rich peptides, which usually containing more than 20 aminoacids, in which intramolecular disulphide bonds determine the three-dimensional structure of the mature protein, and (ii) Group II including cysteine-poor peptides, also called "small post-translationally modified peptides" (SPTMPs) and which are characterized by the small size of the mature peptide (i.e., lower than 20 amino acids), resulting from proteolytic processes, and structurally they contain proline residues and post-translational modifications. Some authors include a third category named as "others" (Lee et al., 2020). SPTMPs share a common tripartite structure characterized by: (i) a signal peptide in the N-terminal region, (ii) a C-terminal region that is usually conserved between family members and corresponds to the mature peptide, and (iii) a variable segment linking the two terminal domains. It has been suggested that SPTMPs have a direct or indirect activity on plant immune regulation. On the other hand, the most of the cysteine-rich peptides discovered are considered antimicrobial peptides in plant-microbe interactions; however, there are some peptides that are mainly involved in plant growth and development and in immune responses (Hu et al., 2018).

4.10.1 Biosynthesis of Plant Peptide Hormones

In general, peptides in plants are derived from larger proteins by proteolytic processing. At present, about 443 different plant peptides have been reported. Most PPHs are derived from a longer precursor with "unknown" biological function, however, some studies point that functional proteins also can be precursors of them. Peptides in plants are synthesized through two ways. A ribosomedependent pathway to produce the so-called ribosomal peptides and, a ribosome-independent pathway to produce non-ribosomal peptides. The latter are produced by the enzymatic activity of nonribosomal peptide synthetases. Some of the ribosomal peptides are post-translationally modified by phosphorylation, acylation, sulphonation, hydroxylation, glycosylation and disulphide



formation, and are degraded by proteolysis (Kastin, 2006; Das et al., 2020). On the other hand, there is evidence that PPHs can also be generated by some microorganisms (insects, fungi and bacteria). For example, the soybean cyst nematode (*Heterodera glycines*) produces peptides able to reach the cytoplasm of plant cells, acting as ligand mimics of plant peptides (Frei et al., 2021).

4.10.2 Applications of Plant Peptide Hormones

In relation to their functionality, a large number of peptides have been identified, such as plant peptides, antibiotic peptides, plant peptides, antibiotic peptides, venom peptides, cancer/antibody peptides and vaccine peptides (Kastin, 2006). On the other hand, the connection of PPHs with food industry and medicine field is evident due to plant are part of dietary of animals and humans. Thus, a significant number of plant protein sources are associated with bioactive peptides. Among effects on human health are lowering of blood pressure levels and inhibition of enzymes within the reninangiotensin aldosterone system, which is a hormonal system that regulates blood pressure, extracellular body volume and the balance of sodium and potassium. In addition, plant-derived bioactive peptides have been identified as cholesterol-lowering, antiinflammatory activity, anticancer, and immunomodulatory activity (Lammi et al., 2014; Butteiger et al., 2016; Hayes and Bleakley, 2018). A summary of potential applications of PPHs is shown in Table 4.

4.11. Nitric oxide (NO)

NO is an inorganic gas that can readily diffuse across cell membranes. Due to its chemical nature, NO is highly reactive, which is produced under normal and stress conditions. NO can interact with various molecules in plant cells, being a key player in the regulation of different processes of plant development, including photomorphogenesis, plant defense, stomatal opening, leaf senescence, flowering and fertilization (Baudouin and Hancock, 2014). In recent years, it has been shown that NO can promote the expression of defense genes in some plants. Many of the regulatory effects of NO have been associated with interactions with other phytohormones. Some examples are seed dormancy and germination, eskotomorphogenic and hottomorphogenic vegetative development, root growth, stomatal closure, pollination, flowering, fruiting or leaf senescence are regulated in some way by interactions between NO and hormones (Arc et al., 2013). In addition, NO is able to act as a regulator of proteins, which can alter their activity, subcellular localization, function, structure or stability. However, it is important to clear that scientific evidence on plant metabolism effects is restricted to processes related to plant stress (León and Costa-Broseta, 2020).

4.11.1 Nitric oxide biosynthesis

Endogenous NO synthesis can occur in organs or cells under stress conditions and subsequently NO diffuses both intra- and intercellularly. Despite multiple reports of synthesis, in plants, its

Agudelo-Morales C.E., et al., J. Sci. Technol. Appl. 10 (2021) 27-65. DOI: 10.34294/j.jsta.21.10.66 ISSN: 0719-8647 | Available: www.jsta.cl

mechanism and the enzymatic sources linked in endogenous NO generation is controversial and it has not been clearly defined. In addition, some studies have indicated that NO synthesis may occur in response to environmental stress caused by salinity, drought, cold, heavy metals and damage caused by biological agents (Ahmad et al., 2018; Nabi et al., 2019).

Among the most accepted biosynthesis pathways are the oxidative and reductive. Within oxidative pathways are included the oxidation of (i) L-arginine by the enzyme NOS-like, (ii) polyamines and (iii) hydroxylamine. On the other hand, the reductive pathways include the reduction of nitrite by: (1) nitrate reductase (NR), (ii) plasma membrane-bound nitrite-NO reductase, (iii) xanthine oxidoreductase (XOR), (iv) cytochrome-c oxidase and/or reductase, and (v) non-enzymatic reduction of nitrite under acidic conditions (i.e., nitrite is protonated to form nitrous acid) in a freely reversible reaction occurring at low pH) (Nabi et al., 2019).

4.11.2 Applications of nitric oxide

In agriculture, NO plays a role in respiratory function, in the electron transport pathways of mitochondria, and activating defense mechanisms by the increase on production of antioxidants in plants exposed to various external disturbances (Zottini et al., 2002). Exogenous NO is used to trigger the activation of antioxidant enzymes and improve crop production under adverse plant conditions (Ahmad et al., 2018). NO has shown to be an endogenous modulator of several plant hormones able to inhibit induced and programmed cell death, but also, it supports stomatal function in several plant species (Magnone et al., 2020).

Table 4. Examples of potential applications of PPHs (Hayes and Bleakley, 2018).

| Effects | Peptide sequence | Source |
|--------------------|-----------------------------|------------------------------------|
| Antihypertensive. | VWIS, VW, IY, and | Rapeseed protein (proteins rich in |
| Angiotensin- | RIY | glutamic acid, aspartic acid, |
| converting- | | leucin and prolinase and contain |
| enzyme | | considerable amounts of all the |
| inhibitors. | | essential amino acids, |
| | | phenylalanine, isoleucine, leucine |
| | | and tryptophan). |
| | QGR, RW, SVR, | Seeds of flax (Linum |
| | QQQG, ASVRI, and | usitatissimum). |
| | GUMRUPI GW/ AV and SV | Soutoon formontation |
| Cytotoxic activity | Bw, AT, and ST Pyrularia | Pyrularia pubera (buffalo put) |
| and anticancer | Thi2 1 | Arabidonsis thaliana (mouse ear |
| | 11112.1 | cress-Brassicaceae) |
| | Mitogenic defensin | Phaseolus vulgaris (common |
| | Ū | bean) |
| | Lunatusin | Phaseolus lunatus (lima bean |
| | | variety) |
| Anticancer | Viscotoxins 1-PS A1, | Viscum album (mistletoe). |
| | A2, A3, B | - <i>i i i i i i i</i> |
| | β-Purothionin | Tricum aestivum (common wheat) |
| | Phoratoxins C, D, E, | Christman mintlatan |
| | anur | (Uninsunas misueloe) |

On the other hand, though NO is known to be endothelium-derived relaxing factor, a vasodilator able to modulate vascular tone, blood pressure and hemodynamics, for applications as nitrate donor therapy for angina, heart failure, pulmonary hypertension and erectile dysfunction. Its origin from plant for these applications is limited due to the possibility to be obtained by different synthetic procedures. However, NO is identified as a powerful antioxidant and anti-inflammatory with antithrombotic actions (Levine et al., 2012).

5. Conclusions and perspectives

One of the most important aspects of the function and regulation of phytohormones in plants is linked to the multiple interactions between them and the responses to the environmental conditions. Although this aspect is not discussed in this review, it is significant when making decisions on the use of different plant hormones, taking into account the plant species to be evaluated, the stage of development, the environmental conditions of the surroundings and the chemical messenger to be used. Despite the large number of publications related to phytohormones, it is important to highlight as this concept has been expanded. A reason it is the advances on contemporary genetic and the development of new techniques for the study at molecular level; thus, it has been possible to establish the origin, function and mechanisms of action of different chemical compounds in plants in greater detail. A special mention must be performed respect to NO and the classical vision due to its inorganic nature.

On the other hand, many of publications that have recently appeared are related to food, biomedical and pharmaceutical effects of plant hormones on animal and human health. In consequence, it is expected that new and novel advances will be performed in the field of food functionals, sensors, and drug industry. The above will surely go hand in hand with the combined use of disciplines such as nanotechnology, molecular dynamics, and biotechnology. However, one of the main limitations is its production and effect in very small quantities. Therefore, the exploration of potential applications will be linked to an increase in the development of instrumental analysis systems.

ж_____

Conflict interest. Authors declare that there is no conflict of interest.

Acknowledgements. Authors thanks to Mindtech s.a.s., Universidad del Valle, Universidad de Córdoba, and Science and Technology Ministry of Colombia for financial support (Postdoctoral fellowships 848-2019 and C.I. 71170).

References

- [1] Abe S., Aika S., Kai T., Takaya K., Kei A., et al. Carlactone is converted to Carlactonoic Acid by MAX1 in Arabidopsis and its methyl ester can directly interact with ATD14 in vitro. Proceedings of the National Academy of Sciences of the United States of America 111 (2014) 18084–18089. <u>https://doi.org/10.1073/pnas.1410801111</u>
- [2] Ahmad P., Ahanger M., Alyemeni N., Wijaya L., Pravej A. Exogenous Application of Nitric Oxide Modulates Osmolyte Metabolism, Antioxidants, Enzymes of Ascorbate-Glutathione Cycle and Promotes Growth under Cadmium Stress in Tomato. Protoplasma 255 (2018): 79–93. <u>https://doi.org/10.1007/s00709-017-1132-x</u>
- [3] Aliche B., Screpanti C., Mesmaeker A., Munnik T., Bouwmeester J. Science and Application of Strigolactones. New Phytologist 227 (2020) 1001–1011. <u>https://doi.org/10.1111/nph.16489</u>
- [4] Andresen M., Cedergreen N. Plant growth is stimulated by tea-seed extract: A new natural growth regulator? HortScience 45 (2010) 1848-1853. <u>https://doi.org/10.21273/hortsci.45.12.1848</u>
- [5] Arc E., Sechet J., Corbineau F., Rajjou L., Marion-Poll L. ABA Crosstalk with Ethylene and Nitric Oxide in Seed Dormancy and Germination. Frontiers in Plant Science 4 (2013) 1-19. <u>https://doi.org/10.3389/fpls.2013.00063</u>
- [6] Babenko L. Jasmonic Acid: Role in Biotechnology and the Regulation of Plants Biochemical Processes. Biotechnologia Acta 8 (2015) 36–51. <u>https://doi.org/10.15407/biotech8.02.036</u>
- [7] Barry S., James G. Ethylene and Fruit Ripening. Journal of Plant Growth Regulation 26 (2007) 143–159. https://doi.org/10.1007/s00344-007-9002-y
- [8] Bassaganya-Riera, J., Skoneczka J., Kingston D., Krishnan A., Misyak S., et al. Mechanisms of Action and Medicinal Applications of Abscisic Acid. Current Medicinal Chemistry 17 (2010) 467–478. <u>https://doi.org/10.2174/092986710790226110</u>

- [9] Baudouin E., Hancock J. Nitric Oxide Signaling in Plants. Frontiers in Plant Science 4 (2014) 1-3. https://doi.org/10.3389/fpls.2013.00553
- [10] BD09269. Phenylacetic acid. <u>https://go.drugbank.com/drugs/DB09269</u>
- [11] Butteiger D.N., Hibberd A.A., McGraw N.J., Napawan N., Hall-Porter J.M., Krul E.S. Soy protein compared with milk protein in a western diet increases gut microbial diversity and reduces serum lipids in golden Syrian hamsters. Journal of Nutrition 146 (2016) 697-705. <u>https://doi.org/10.3945/jn.115.224196</u>
- [12] Castro A., de Souza C., Fontanetti C. Herbicide 2,4-D: A Review of Toxicity on Non-Target Organisms. Water, Air, and Soil Pollution. 228 (2017) 1–12. <u>https://doi.org/10.1007/s11270-017-3301-0</u>
- [13] Chamorro A., Martínez L., Fernández C., Mosquera T. Evaluación de diferentes concentraciones de algunos reguladores de crecimiento en la multiplicación y enraizamiento in vitro de Limonium var. Misty blue. Agronomía Colombiana. 25 (2007) 47-53. <u>https://revistas.unal.edu.co/index.php/agrocol/article/view/14396</u>
- [14] Clouse S. Brassinosteroids. The Arabidopsis Book. American Society of Plant Biologists. 9 (2011) 1-28. https://doi.org/10.1199/TAB.0151
- [15] Chen Y., Grimplet J., David K., et al. Ethylene receptors and related proteins in climacteric and non-climacteric fruits. Plant Science, 276 (2018) 63-72. <u>https://doi.org/10.1016/j.plantsci.2018.07.012</u>
- [16] Chen J., Yang J., Ma L. et al. Structure-antioxidant activity relationship of methoxy, phenolic hydroxyl, and carboxylic acid groups of phenolic acids. Scientific Reports. 10 (2020) 2611. <u>https://doi.org/10.1038/s41598-020-59451-z</u>
- [17] Colebrook E., Thomas S., Phillips A., Hedden P. The Role of Gibberellin Signalling in Plant Responses to Abiotic Stress. Journal of Experimental Biology. 217 (2014) 67-75. <u>https://doi.org/10.1242/jeb.089938</u>
- [18] Cowling R., Kamiya Y., Seto H., Harberd P. Gibberellin Dose-Response Regulation of GA4 Gene Transcript Levels in Arabidopsis. Plant Physiology. 117 (1998) 1195–1203. <u>https://doi.org/10.1104/pp.117.4.1195</u>
- [19] Csaba G, Darvas S, László V. Effects of treatment with the plant hormone gibberellin on neonatal rats. Acta Biology Medical Ger. 36 (1977) 1487-1488.
- [20] Darwin, C. General considerations on the movements and growth of seedling plants. In the Power of Movement in Plants (Cambridge Library Collection Darwin, Evolution and Genetics. (1880) 67-128. https://doi.org/10.1017/CBO9780511693670.003
- [21] Das D., Jaiswal M., Khan F., Ahamad S., Kumar S. PlantPepDB: A Manually Curated Plant Peptide Database. Scientific Reports. 10 (2020.) 1–8. <u>https://doi.org/10.1038/s41598-020-59165-2</u>
- [22] Davies, P. J. Their nature, occurrence, and functions. Plant Hormones. Springer. (2010). 1–15. <u>https://doi.org/10.1007/978-1-4020-2686-7_1</u>
- [23] Durmuş, N., Kadioğlu A. Reduction of Paraquat Toxicity in Maize Leaves by Benzyladenine. Acta Biologica Hungarica. 56 (2005) 97–107. <u>https://doi.org/10.1556/ABiol.56.2005.1-2.10</u>
- [24] Ekinci D., Şentürk M., Kfrevioğlu O. Salicylic acid derivatives: Synthesis, features and usage as therapeutic tools. Expert Opinion on Therapeutic Patents. Taylor & Francis. 21 (2011) 1831-1841. <u>https://doi.org/10.1517/13543776.2011.636354</u>
- [25] Enders T., Strader L. Auxin Activity: Past, Present, and Future. American Journal of Botany 102 (2015) 180–96. https://doi.org/10.3732/ajb.1400285

- [26] Erb Ma., Kliebenstein D. Topical Review Plant Secondary Metabolites as Defenses, Regulators, and Primary Metabolites: The Blurred Functional Trichotomy. Plant Physiology 184 (2020) 184: 39–52. <u>https://doi.org/10.1104/pp.20.00433</u>
- [27] Erin N., Afacan B., Ersoy Y., Ercan F., Balci M.K. Gibberellic acid, a plant growth regulator, increases mast cell recruitment and alters Substance P levels. Toxicology. 254 (2008) 75-81. <u>https://doi.org/10.1016/j.tox.2008.09.020</u>
- [28] Ewang-Emukowhate M., Nair D., Caplin M. The role of 5-hydroxyindoleacetic acid in neuroendocrine tumors: the journey so far. International Journal of Endocrine oncology. 6 (2019). <u>https://doi.org/10.2217/ije-2019-0001</u>
- [29] Feelders R., Hofland L., Kwekkeboom D.J., et al. Neuroendocrine Tumors. In: Handbook of Neuroendocrinology. Elsevier. (2012).
- [30] Ferro N., Bultinck P., Gallegos A., Jacobsen H., Carbo-Dorca R., et al. Unrevealed structural requirements for auxin-like molecules by theoretical and experimental evidences. Phytochemistry. 68 (2007) 237–250. <u>https://doi.org/10.1016/j.phytochem.2006.10.006</u>
- [31] Finkelstein Ruth., Reeves W., Ariizumi T., Steber C. Molecular Aspects of Seed Dormancy. Annual Review of Plant Biology. Annu Rev Plant Biol. 59 (2008) 387-415. <u>https://doi.org/10.1146/annurev.arplant.59.032607.092740</u>
- [32] Finkelstein, Ruth. Abscisic Acid Synthesis and Response. The Arabidopsis Book. (2013) 1-36. <u>https://doi.org/10.1199/tab.0166</u>
- [33] Fiormarkets. Plant growth regulators market by product, application, region, global industry analysis, market size, share, growth, trends, and forecast 2020 to 2027. Retrieved January 2021. <u>https://www.fiormarkets.com/report/plant-growth-regulators-market-by-product-auxins-cytokinins-418650.html</u>
- [34] FlescherOrit E. Jasmonate pharmaceutical composition for treatment of cancer, issued April 4, (2001). https://patents.google.com/patent/US20020173470A1/en
- [35] Frei dit N., Favery B. Plant-Parasitic Nematode Secreted Peptides Hijack a Plant Secretory Pathway. New Phytologist. 229 (2021) 11-13. <u>https://doi.org/10.1111/nph.16842</u>
- [36] Gancheva S., Malovichko Y., Poliushkevich L., Dodueva I., Lutova L. Plant Peptide Hormones. Russian Journal of Plant Physiology. 66 (2019) 171-189. <u>https://doi.org/10.1134/S1021443719010072</u>
- [37] Gao X., Zhang Y., He Z., Fu X. Gibberellins. In Hormone Metabolism and Signaling in Plants, (2017) 107–60. Elsevier Inc. https://doi.org/10.1016/B978-0-12-811562-6.00004-9
- [38] Garcés V., Palencia M., Combatt, E. Development of bacterial inoculums based on biodegradable hydrogels for agricultural applications. Journal of Science with Technological Applications. 2 (2017) 13-23. <u>https://doi.org/10.34294/j.jsta.17.2.11</u>
- [39] Gawienowski A.M., Stadnicki S.S., Stacewicz-Sapuntzakis M. Androgenic properties of gibberellic acid in the chick comb bioassay. Experientia 33 (1977) 1544–1545. <u>https://doi.org/10.1007/BF01918862</u>
- [40] Ghasemi A., Sajjadi S., Parang K. A Review (Research and Patents) on Jasmonic Acid and Its Derivatives. Archiv Der Pharmazie. 347 (2014) 229–39. <u>https://doi.org/10.1002/ardp.201300287</u>
- [41] Ghorbani S., Fernandez A., Hilson P., Beeckman T. Signaling Peptides in Plants. Cell & Developmental Biology. 3 (2014) 1-11. https://doi.org/10.4172/2168-9296.1000141
- [42] Grierson D. 100 Years of Ethylene A Personal View. In the plant hormone ethylene, Wiley-Blackwell. 44 (2012) 1–17. https://doi.org/10.1002/9781118223086.ch1
- [43] Gupta R., Chakrabarty S. Gibberellic Acid in Plant: Still a Mystery Unresolved. Plant Signaling and Behavior. 8 (2013) 255041-255045. <u>https://doi.org/10.4161/psb.25504</u>



- [44] Gupta R., Pizarro L., Leibman-Markus M., Marash I., Bar M. Cytokinin response induces immunity and fungal pathogen resistance and modulates trafficking of the PRR LeEIX2 in Tomato. Molecular Plant Pathology 21 (2020): 1287–1306. <u>https://doi.org/10.1111/mpp.12978</u>
- [45] Halouzka R., Zeljković S., Klejdus B., Tarkowski P. Analytical Methods in Strigolactone Research." Plant Methods. BioMed Central Ltd. 16 (2020) 76-89. <u>https://doi.org/10.1186/s13007-020-00616-2</u>
- [46] Hasan M., Razvi S., Kuerban A., Balamash K., Al-Bishri W., et al. Strigolactones-A Novel Class of Phytohormones as Anti-Cancer Agents. Journal of Pesticide Science. Pesticide Science Society of Japan. 43 (2018) 168-172. <u>https://doi.org/10.1584/jpestics.D17-090</u>
- [47] Hayat, S., Ahmad A. Salicylic Acid: Biosynthesis, Metabolism and Physiological Role in Plants. A Plant Hormone. Springer, (2007) 1-14. <u>https://doi.org/10.1007/1-4020-5184-0_1</u>
- [48] Hayes M., Bleakley S. Peptides from plants and their applications. In: Koutsopoulos S. (Ed). Peptide Applications in Biomedicine, Biotechnology and Bioengineering. Elsevier, 21 (2018) 603-622. <u>https://doi.org/10.1016/B978-0-08-100736-5.00025-9</u>
- [49] Heo H., Hong S., Cho H., Hong B., Kim H., et al. Inhibitory effect of zeatin, isolated from fiatoua villosa, on acetylcholinesterase activity from PC12 Cells. Molecules and Cells. 13 (2002) 113–17.
- [50] Hosseinchi M., Soltanalinejad F., Najafi G., Roshangar L. Effect of gibberellic acid on the quality of sperm and in vitro fertilization outcome in adult male rats. Veterinary Resource Forum, 4 (2013) 259-264.
- [51] Hu, Z., Zhang H., Shi K. Plant peptides in plant defense responses. Plant signaling and behavior. Taylor and Francis Inc. 13 (2018) 1475175-1475180. <u>https://doi.org/10.1080/15592324.2018.1475175</u>
- [52] Iqbal N., Khan N., Ferrante A., Trivellini A., Francini A., et al. Ethylene role in plant growth, development and senescence: interaction with other phytohormones. Frontiers in plant science. 8 (2017) 475-503. <u>https://doi.org/10.3389/fpls.2017.00475</u>
- [53] Ivanchenko M., Napsucialy-Mendivil S., Dubrovsky J. Auxin-Induced Inhibition of Lateral Root Initiation Contributes to Root System Shaping in Arabidopsis Thaliana. Plant Journal. 64 (2010) 740–52. <u>https://doi.org/10.1111/j.1365-313X.2010.04365.x</u>
- [54] Jabłońska-Trypuć Agata., Matejczyk M., Czerpak R. N6-Benzyladenine and Kinetin Influence Antioxidative Stress Parameters in Human Skin Fibroblasts. Molecular and Cellular Biochemistry. 413 (2016) 97–107. <u>https://doi.org/10.1007/s11010-015-2642-5</u>
- [55] Jaillais Y., Chory J. Unraveling the Paradoxes of Plant Hormone Signaling Integration. Nature Structural and Molecular Biology. 17 (2010): 642–45. <u>https://doi.org/10.1038/nsmb0610-642</u>
- [56] Jiang K., Asami T. 2018. Chemical regulators of plant hormones and their applications in basic research and agriculture. Bioscience, Biotechnology and Biochemistry. Japan Society for Bioscience Biotechnology and Agrochemistry. 82 (2018) 1265-1300. https://doi.org/10.1080/09168451.2018.1462693
- [57] Karcz, W. A comparison of the effects of IAA and 4-Cl-IAA on growth, proton secretion and membrane potential in maize coleoptile segments. Journal of Experimental Botany. 53 (2002) 1089–1098. <u>https://doi.org/10.1093/jexbot/53.371.1089</u>
- [58] Kastin A. Handbook of Biologically Active Peptides. Handbook of Biologically Active Peptides. Elsevier Inc. (2006) 16-40. https://doi.org/10.1016/B978-0-12-369442-3.X5001-6
- [59] Kögl F., Haagen-Smit A., Erxleben H. Über Ein Neues Auxin ('Hetero-Auxin') Aus Harn. 11. Mitteilung Über Pflanzliche Wachstumsstoffe. Hoppe-Seyler's Zeitschrift Fur Physiologische Chemie. 228 (1934) 90–103. <u>https://doi.org/10.1515/bchm2.1934.228.1-2.90</u>
- [60] Kohli S., Bhardwaj A., Bhardwaj V., Sharma A, Kalia N., et al. Therapeutic potential of Brassinosteroids in biomedical and clinical research. Biomolecules. MDPI AG. 10 (2020) 572-599. <u>https://doi.org/10.3390/biom10040572</u>

- [61] Kogan G., Šoltés L., Stern R. et al. Hyaluronic acid: a natural biopolymer with a broad range of biomedical and industrial applications. Biotechnology Letter, 29 (2007) 17–25. <u>https://doi.org/10.1007/s10529-006-9219-z</u>
- [62] Korasick D., Enders T., Strader L. Auxin biosynthesis and storage forms. Journal of Experimental Botany. 64 (2013) 2541-2555. https://doi.org/10.1093/jxb/ert080
- [63] Kujiyama A., Takeuchi T. Application of indoleacetic acid-imprinted polymer to solid phase extraction. Analytical Chimica Acta, 395 (1999) 251-255. <u>https://doi.org/10.1016/S0003-2670(99)00349-9</u>
- [64] Lammi C., Zanoni C., Scigliuolo G.M., D'Amato A., Arnoldi A. Lupin peptides lower low-density lipoprotein (LDL) cholesterol through an up-regulation of the LDL receptor/sterol regulatory element binding protein (SREBP2) Pathway at HepG2 cell line. Journal of Agricultural and Food Chemistry. 62 (2014) 7151-7159. <u>https://doi.org/10.1021/jf500795b</u>
- [65] Lee K., Kwon D., Song J., Seo H. Production mechanisms, structural features and post-translational modifications of plant peptides. Journal of Plant Biology. Springer. 63 (2020) 259-265. <u>https://doi.org/10.1007/s12374-020-09255-5</u>
- [66] León J., Costa-Broseta A. Present Knowledge and controversies, deficiencies, and misconceptions on nitric oxide synthesis, sensing, and signaling in plants. Plant Cell and Environment. Blackwell Publishing Ltd. 43 (2020) 1-15. https://doi.org/10.1111/pce.13617
- [67] Lerma T., Combatt E., Palencia M. 2018. Soil-mimicking hybrid composites based on clay, polymers and nitrogen-fixing bacteria for the development of remediation systems of degraded soil. Journal of Science with Technological Applications. 4 (2018) 17-27. <u>https://doi.org/10.34294/j.jsta.18.4.27</u>
- [68] Levine A.B., Punihaole D., Levine T.B. Characterization of the Role of Nitric Oxide and Its Clinical Applications. Cardiology, 122 (2012). <u>https://doi.org/10.1159/000338150</u>
- [69] Li H., Hao R., Wu S., Guo P., Chen C., et al. 2011. Occurrence, function and potential medicinal applications of the phytohormone abscisic acid in animals and humans. Biochemical Pharmacology. 82 (2011) 701-712. <u>https://doi.org/10.1016/j.bcp.2011.06.042</u>
- [70] Li H., Wu H., Qi Q., Li H., Li Z., et al. Gibberellins play a role in regulating Tomato fruit ripening. Plant and Cell Physiology. 60 (2019) 1619–1629. <u>https://doi.org/10.1093/pcp/pcz069</u>
- [71] MacMillan J. Occurrence of gibberellins in vascular plants, fungi, and bacteria. Journal of Plant Growth Regulation. 20 (2001) 387–442. <u>https://doi.org/10.1007/s003440010038</u>
- [72] Magnone M., Sturla L., Guida L., Spinelli S, Begani G., et al. Abscisic Acid: a conserved hormone in plants and humans and a promising aid to combat prediabetes and the metabolic syndrome. Nutrients. 12 (2020) 1724-1739. https://doi.org/10.3390/nu12061724
- [73] Maruri-López I., Aviles-Baltazar N., Buchala A., Serrano M. 2019. Intra and extracellular journey of the phytohormone salicylic acid. Frontiers in Plant Science. 10 (2019) 423-438. <u>https://doi.org/10.3389/FPLS.2019.00423</u>
- [74] Marzec M., Muszynska A. In silico analysis of the genes encoding proteins that are involved in the biosynthesis of the RMS/MAX/D pathway revealed new roles of Strigolactones in plants. International Journal of Molecular Sciences. 16 (2015) 6757–6782. <u>https://doi.org/10.3390/ijms16046757</u>
- [75] Mitchell J., Mandava N., Worley J., Plimmer J., Smith M. Brassins-a new family of plant hormones from rape pollen. Nature. 225 (1970) 1065–1066. <u>https://doi.org/10.1038/2251065a0</u>
- [76] Nabi R., Tayade R., Hussain A., Kulkarni K., Imran Q., et al. 2019. Nitric oxide regulates plant responses to drought, salinity, and heavy metal stress. Environmental and Experimental Botany. 161 (2019) 120–133. https://doi.org/10.1016/j.envexpbot.2019.02.003



- [77] Ohkuma K., Lyon J, Addicott F., Smith O. Abscisin II, an abscission-accelerating substance from young cotton fruit. Science. 142 (1963) 1592–1593. <u>https://doi.org/10.1126/science.142.3599.1592</u>
- [78] Ortolá, A., Monerri C., Guardiola JL. The use of naphthalene acetic acid as a fruit growth enhancer in Satsuma mandarin: a comparison with the fruit thinning effect. Scientia Horticulturae. 47 (1991) 15-25. <u>https://doi.org/10.1016/0304-4238(91)90023-R</u>
- [79] Oshchepkov M., Kalistratova A., Savelieva E., Romanov G., Bystrova N., et al. Natural and synthetic cytokinins and their applications in biotechnology, agrochemistry and medicine. Russian Chemical Reviews. 89 (2020) 787–810. https://doi.org/10.1070/rcr4921
- [80] Osugi, A., Sakakibara, H. Q&A: How do plants respond to cytokinins and what is their importance?. BMC Biol. 13 (2015) 102-112. https://doi.org/10.1186/s12915-015-0214-5
- [81] Overbeek J. Growth-Regulating substances in plants. Annual Review of Biochemistry. 13 (1944) 631–66. https://doi.org/10.1146/annurev.bi.13.070144.003215
- [82] Overvoorde P., Fukaki H., Beeckman T. Auxin Control of Root Development. Cold Spring Harbor Perspectives in Biology. 2 (2010) 1537-1554. <u>https://doi.org/10.1101/cshperspect.a001537</u>
- [83] Pattyn J., Vaughan-Hirsch J., Van de Poel B. The regulation of ethylene biosynthesis: a complex multilevel control circuitry. New Phytologist. 229 (2021) 770–82. <u>https://doi.org/https://doi.org/10.1111/nph.16873</u>
- [84] Peres A., Soares J., Tavares R., Righetto G., Zullo M., et al. Brassinosteroids, the sixth class of phytohormones: a molecular view from the discovery to hormonal interactions in plant development and stress adaptation. International Journal of Molecular Sciences. 15 (2019) 331-363. <u>https://doi.org/10.3390/ijms20020331</u>
- [85] Rademacher W. Plant growth regulators: backgrounds and uses in plant production. Journal of Plant Growth Regulation. 34 (2015) 845–72. <u>https://doi.org/10.1007/s00344-015-9541-6</u>
- [86] Ruan J., Zhou Y., Zhou M., Yan J., Khurshid M., et al. Jasmonic Acid signaling pathway in plants. International Journal of Molecular Sciences. 20 (2019) 2479-2494. <u>https://doi.org/10.3390/ijms20102479</u>
- [87] Ruzić D., Vujović T., Cerović R, Djordjević M. Potential application of Jasmonic acid in in vitro rooting of low vigorous pear and cherry rootstocks. Acta Horticulturae. 1099 (2015) 895–900. <u>https://doi.org/10.17660/ActaHortic.2015.1099.114</u>
- [88] Sah S., Reddy K., Li J. Abscisic Acid and abiotic stress tolerance in crop plants. Frontiers in Plant Science. 7 (2016) 571- 592. https://doi.org/10.3389/fpls.2016.00571
- [89] Sakthivel P., Sharma N., Klahn P., Gereke M., Bruder D. Abscisic Acid: A phytohormone and mammalian cytokine as novel pharmacon with potential for future development into clinical applications. Current Medicinal Chemistry. 23 (2016) 1549–70. https://doi.org/10.2174/0929867323666160405113129
- [90] Salazar-Cerezo S., Martínez-Montiel N., García-Sánchez J., Pérez-Terrón R., Martínez-Contreras R. Gibberellin biosynthesis and metabolism: a convergent route for plants, fungi and bacteria. Microbiological Research. 208 (2018) 85-98. https://doi.org/10.1016/j.micres.2018.01.010
- [91] Sanower M., Urbi Z. Effect of Naphthalene Acetic Acid on the adventitious rooting in shoot cuttings of Andrographis Paniculata (burm.f.) wall. ex nees: an important therapeutical herb. International Journal of Agronomy. (2016) 1-6. https://doi.org/10.1155/2016/1617543
- [92] Smith S., Li C., Li J. Hormone Function in Plants. In hormone metabolism and signaling in plants. Elsevier Inc. (2017) 1-38. https://doi.org/10.1016/B978-0-12-811562-6.00001-3
- [93] Spielmeyer W., Ellis M., Chandler P. Semidwarf (Sd-1), 'Green revolution' rice, contains a defective Gibberellin 20-Oxidase gene. Proceedings of the National Academy of Sciences of the United States of America. 99 (2002) 9043–9048. https://doi.org/10.1073/pnas.132266399

- [94] Stirk W., van Staden J. Flow of Cytokinins through the environment. plant growth regulation. Springer. 62 (2010) 101-116. https://doi.org/10.1007/s10725-010-9481-x
- [95] Taiz L., Zeiger E. Plant Physiology. 3rd ed. Vol. 1. Sinauer Associates. (2003) 1-690. https://doi.org/10.1093/aob/mcg079
- [96] Thimann K., Auxins and the inhibition of plant growth. Biological Reviews. 14 (1939) 314–337. <u>https://doi.org/10.1111/j.1469-185X.1939.tb00937.x</u>
- [97] Thimann K., Growth hormones in plants. Journal of the Franklin Institute. 229 (1940) 337–346. <u>https://doi.org/10.1016/S0016-0032(40)90872-9</u>
- [98] Toyomasu T., Kawaide H., Mitsuhashi W., Inoue Y., Kamiya Y. Phytochrome regulates gibberellin biosynthesis during germination of photoblastic lettuce seeds. Plant Physiology. 118 (1998) 1517–23. <u>https://doi.org/10.1104/pp.118.4.1517</u>
- [99] Tsavkelova E., Klimova S., Cherdyntseva, T., Netrusov A. Microbial producers of plant growth stimulators and their practical use: A review. Applied Biochemistry and Microbiology. 42 (2006) 117-126. <u>https://doi.org/10.1134/S0003683806020013</u>
- [100] Valitova J., Sulkarnayeva A., Minibayeva F. Plant Sterols: diversity, biosynthesis, and physiological functions. Biochemistry (Moscow). 81 (2016) 819-834. <u>https://doi.org/10.1134/S0006297916080046</u>
- [101] Vandenbussche F., Van Der Straeten D. The role of Ethylene in plant growth and development. In the Plant Hormone Ethylene, 44 (2012) 219–241. <u>https://doi.org/10.1002/9781118223086.ch9</u>
- [102] Vanneste S., Friml J. Auxin: a trigger for change in plant development. Cell. 136 (2009) 1005-1016. https://doi.org/10.1016/j.cell.2009.03.001
- [103] Villanueva F., Ávila M., Mansilla A., Abades S., Cáceres J. Efecto de Auxinas y Citoquinas en el cultivo de tejido de Ahnfeltia Plicata (Hudson) Fries, 1836 (Ahnfeltiales Rhodophyta) de la región de magallanes. Anales del Instituto de la Patagonia. 41 (2013) 99–111. <u>https://doi.org/10.4067/s0718-686x2013000100009</u>
- [104] Voller J., Béres T., Zatloukal M., Džubák P., Hajdúch M., et al. Anti-Cancer Activities of Cytokinin ribosides. Phytochemistry Reviews. 18 (2019) 1101-1113. <u>https://doi.org/10.1007/s11101-019-09620-4</u>
- [105] Wang J., Song L., Gong X., Xu J., Li M. Functions of Jasmonic Acid in Plant Regulation and Response to Abiotic Stress. International Journal of Molecular Science, 21 (2020) 1446. <u>https://doi.org/10.3390/ijms21041446</u>
- [106] Wang B., Wang Y., Li J. Strigolactones. In hormone metabolism and signaling in plants, (2017) 327–359. https://doi.org/10.1016/B978-0-12-811562-6.00010-4
- [107] Werner T., Motyka V., Strnad M., Schmülling T. Regulation of plant growth by cytokinin. Proceedings of the National Academy of Sciences of the United States of America. 98 (2001) 10487-10492. <u>https://doi.org/10.1073/pnas.171304098</u>
- [108] Woodward A., Bartel B. 2005. Auxin: regulation, action, and interaction. Annals of Botany. 95 (2005) 707-735. https://doi.org/10.1093/aob/mci083
- [109] Xiong L., Zhu J. Regulation of Abscisic Acid biosynthesis. Plant Physiology. American Society of Plant Biologists. 133 (2003) 29-36. <u>https://doi.org/10.1104/pp.103.025395</u>
- [110] Xu Y., Gage D., Zeevaart J. Gibberellins and stem growth in Arabidopsis Thaliana: Effects of photoperiod on expression of the GA4 and GA5 Loci. Plant Physiology 114 (1997) 1471–1176. <u>https://doi.org/10.1104/pp.114.4.1471</u>
- [111] Yan Y., Borrego E, Kolomiets M. Jasmonate biosynthesis, perception and function in plant development and stress responses. In Lipid Metabolism. (2013). <u>https://doi.org/10.5772/52675</u>
- [112] Zhang Y., Lo Y., Hu Y., Li G., Chen Y. Preparation of magnetic indole-3-acetic acid imprinted polymer beads with 4-vinylpyridine and β-cyclodextrin as binary monomer via microwave heating-initiated polymerization and their application to trace analysis of auxins in plant tissues. Journal of Chromatography A. 19 (2010) 7337-44. <u>https://doi.org/10.1016/j.chroma.2010.09.059</u>

- [113] Zhao Y. Auxin biosynthesis: A simple two-step pathway converts tryptophan to Indole-3-Acetic Acid in plants. In Molecular Plant, 5 (2012) 334–38. <u>https://doi.org/10.1093/mp/ssr104</u>
- [114] Zieniuk B., Woloszynowska M., Białecka-Florjańczyk W., Fabiszewska A. Synthesis of Industrially Useful Phenolic Compounds Esters by Means of Biocatalysts Obtained Along with Waste Fish Oil Utilization. Sustainability. 2020, 12 (14) 5804. <u>https://doi.org/10.3390/su12145804</u>
- [115] Zocchi E, Hontecillas R, Leber A, et al. Abscisic Acid: A Novel Nutraceutical for Glycemic Control. Frontiers in Nutrition, 4 (2017) 24. <u>https://doi.org/10.3389/fnut.2017.00024</u>
- [116] Zottini M., Formentin E., Scattolin M., Carimi F., Lo Schiavo F., et al. Nitric Oxide affects plant mitochondrial functionality in vivo. FEBS Letters. 515 (2002) 75–78. <u>https://doi.org/10.1016/S0014-5793(02)02438-9</u>
- [117] Zullo M., Adam G. Brassinosteroid phytohormones structure, bioactivity and applications. Brazilian Journal of Plant Physiology. 14 (2002) 143-181. <u>https://doi.org/10.1590/S1677-04202002000300001</u>

ж.

© MT-Pallantia Publisher (2021)

