Mechanisms of Plant Growth and Productivity: Investigating Biological Processes at the Molecular, Cellular, and Whole-Organism Levels

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Abstract

Arable land for agricultural production has been continuously decreasing over the past several years as a result of urban expansion. Although the output of agricultural produce has not been impacted in terms of quantity, innovations must be made to ensure that food production keeps up with the growing population. However, it is essential to first understand the mechanisms and interactions within plants that drive plant growth. This secondary research paper analyzes the biological processes that aid in plant growth and productivity, looking at the different mechanisms on a molecular, cellular, and whole-organism level. Specifically, photosynthesis, germination, and auxin-cytokinin signaling were the main processes discussed in this particular research paper. Through this analysis, it can be established that all three selected processes play an important role in plant development, with each contributing to the functionality of several key mechanisms in plants. Photosynthesis is the fundamental process through which the plant derives energy from light and sustains growth. Auxins and cytokinins regulate plant development, specifically in the roots and shoots, through an antagonistic relationship. Germination facilitates the transition of a plant from a seed to a sprout. A variety of peer-reviewed articles were utilized throughout the review process in order to synthesize a fully encompassing perspective, and bias was mitigated through the usage of articles from a variety of journals, years, and researchers. Certain limitations may reduce the effectiveness of this article, including the limited species of plants used in the examined sources. This research was conducted with the aim of connecting biological processes in order to understand their potential for plant development and crop yield. Therefore, this research could be used to aid in promoting the fulfillment of the United Nations Sustainable Development goals of no poverty, zero hunger, and good health and well-being.

Introduction

This paper aims to investigate three biological processes, specifically, photosynthesis, germination, and hormone signaling, at the molecular, cellular, and whole-organism levels, contributing to plant growth and productivity for food production. Being able to understand the biological processes that drive plant growth and food production could lead to novel agricultural techniques in both rural and urban settings. These improved agricultural techniques can help hasten the achievement of several of the key United Nations sustainable development goals through increased production of food.

A variety of biological processes are utilized by plants to support proper growth and development. Photosynthesis, the antagonistic relationship shared by auxins and cytokinins, and germination are several significant processes related to plant growth that will be examined throughout this review. Specifically, photosynthesis is a unique process found within plants, algae, and photosynthetic bacteria that allows for the synthesis of organic molecules from carbon dioxide, sunlight, and water. This process occurs in two separate stages: the light-dependent reactions and the Calvin cycle. Respectively, they occur in the thylakoid membrane and stroma of plastids for photosynthetic eukaryotes (Stirbet et al., 2020). Auxins and cytokinins are two pivotal hormones responsible for regulating plant growth and development while also maintaining mutual feedback to regulate each other's synthesis (Jones & Ljung, 2011). Germination is a process by which seeds are able to mature into seedlings following the fulfillment of specific factors such as temperature and water (Bennett, 2021). These processes were chosen specifically due to their pivotal roles in plant growth as well as misconceptions about the complexities of each. For example, photosynthesis is often wrongly assumed to be a simple process, and auxin and cytokinin signaling is commonly seen as only "antagonistic," when in reality, the two hormones synergize to properly perform their roles. As a result, it is vital that we fully understand the mechanisms driving each process at the molecular, cellular, and whole-organism levels, and how we can optimize them to aid in agricultural production.

Problem Statement

As arable land for agriculture steadily decreases as a result of urban expansion, it is becoming increasingly essential to expand the overall production of plants by understanding and enhancing their core biological processes. According to the American Farmland Trust, nearly four million and seven million acres of farmland were converted to urban and residential land use, respectively, between 2001 and 2016 (Brain et al., 2023). These losses highlight the importance of strengthening plant growth and development for food production by understanding the foundational biological processes responsible for plant growth.

Methodology

This study aims to investigate photosynthesis, auxin and cytokinin signaling, and germination at the molecular, cellular, and whole-organism levels by utilizing a secondary research strategy. A secondary research strategy was used specifically because of its ability to analyze existing data to answer new research questions (Kelly, 2024). Through this, perspectives and information of several different authors were synthesized to create a comprehensive overview of the mechanisms behind plant growth and productivity. Data was collected from credible, peer-reviewed databases such as Google Scholar, the National Institutes of Health, and ScienceDirect to secure reliability. Furthermore, only contemporary sources were examined to ensure information was accurate and up to date with novel technologies. Each source was analyzed using content analysis to identify themes and connections within processes, such as the antagonistic relationship between auxins and cytokinins. Potential biases of sources were mitigated by drawing sources from several different authors and databases, therefore guaranteeing that different perspectives were acknowledged during the research process. However, there are some potential limitations to our methodology. For auxin and cytokinin signaling as well as germination, many studies focused on those biological processes specifically in *Arabidopsis*. Therefore, data about these processes might not be as accurate when considering other types of plants. Furthermore, it is impossible to fully encompass all aspects of the three biological processes focused on in this study, especially when considering new discoveries being made concurrently.

Background

Photosynthesis

Oxygenic photosynthesis is a complex process induced by the absorption of light that can be separated into two foundational steps: the light-dependent reaction and the Calvin cycle. Among most plants, the light-dependent reactions occur within the thylakoid membrane, a highly folded membrane compartment that contains chlorophyll, while the Calvin cycle occurs within the stroma, a fluid found outside of the thylakoid membrane (Johnson, 2016).

The light-dependent reactions are initiated through the absorption of light by a pigment molecule found within photosystem II (PSII). This energy is then transferred to P680, a pigment complex comprising a pair of chlorophyll molecules that serve as electron donors, which can subsequently be transferred to an acceptor molecule, pheophytin. Following this, P680 becomes positively charged and requires an additional electron to return to its ground state (Choi, 2022). This can occur due to an enzyme embedded within PSII named the oxygen-evolving complex (OEC), which removes an electron from a nearby water molecule during a process called photolysis and donates it to P680 (Johnson, 2016). As a result of this process, the water molecule is split into oxygen, a byproduct, and hydrogen (H+), which can then be used to synthesize adenosine triphosphate (ATP) by establishing an electrochemical gradient. The electron is then carried by plastoquinone, a transfer agent, to cytochrome, an electron connector, which allows the electron to reach photosystem I (PSI) after passing through plastocyanin (Johnson, 2016). Additionally, H+ ions are able to enter the thylakoid interior from the stroma through both plastoquinone and cytochrome, which creates an H+ gradient. This movement is done through active transport with energy supplied from the electron transport chain. Throughout this process, the high-energy electrons lose energy until it can become recharged by PSI. After the electron successfully reaches PSI, it is passed through pigment molecules until it reaches P700, a pair of pigment molecules that recharge the electron through photon energy (Johnson, 2016). Subsequently, the recharged electrons are passed to an acceptor molecule, Chlorophyll A_0, which allows the energized electron to be passed to several protein complexes. This process allows for the reduction of NADP+ into NADPH (Moolna, 2010). Concurrently, ATP synthase is gaining energy from the passage of H+ through the thylakoid membrane, therefore allowing it to phosphorylate adenosine diphosphate (ADP) into ATP (Cardona, 2016). This process allows for the production of both ATP and NADPH, which are essential reactants used in the Calvin cycle.

While the light-dependent reactions capture light energy and convert it into chemical energy in the form of ATP and NADPH, the Calvin cycle instead uses that stored energy to fix carbon dioxide into G3P, which can later form glucose and other carbohydrates. The Calvin cycle can be divided into three main stages: carbon fixation, reduction, and regeneration. Carbon fixation begins with the absorption of CO_2 through the mesophyll layer of leaves. CO_2 then diffuses into mesophyll cells and subsequently into the stroma (Gil, 2024). Rubisco catalyzes the attachment of CO_2 to ribulose biphosphate (RuBP), creating an unstable six-carbon sugar. This molecule splits into two three-carbon molecules, 3-PGA. During reduction, 3-PGA gains a phosphate group from ATP (Singh, 2023). This allows the molecule to receive two electrons from NADPH while also losing its second phosphate group, effectively forming G3P. Then, G3P is either turned back into RuBP through a series of enzymatic processes or removed from the cycle to synthesize glucose (Singh, 2023).

Photosynthesis contributes greatly to plant growth because of the processes found at the molecular, cellular, and whole-organism levels. At the molecular level, photosynthesis involves a variety of molecules that can be illustrated with the following equation: $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$ (Powell, 2020). Additionally, the process as a whole involves proteins such as P680, FNR, and RuBP, the items required to complete the anabolic process. The energy produced as a result of this process would not be possible without these features; therefore, they play a vital role in the steps required for plant growth.

At the cellular level, photosynthesis contributes to plant development by providing cells with the energy required for plant tissue growth. Specifically, glucose can be used for cellular respiration, the production of oils and fats, the production of cellulose, and the eventual synthesis of proteins (Powell, 2020). At the whole-organism level, the energy produced as a result of photosynthesis is used across the plant in a variety of locations to aid in both the overall maintenance and the growth of the organism (Powell, 2020). This growth will sustain the plant and allow it to thrive in its given environment.

Hormone Signaling: Auxins and Cytokinins

Auxins and cytokinins are plant hormones that create a molecular balance in order to orchestrate growth. Auxins, which are produced in shoot tips as well as younger leaves, aid in directing the growth; their primary role is to promote cell elongation, apical dominance, and prompt root growth (Michaels et al., 2022). Following the synthesis of the hormone, auxins are generally transported to certain parts of the cell by the polar localization of PIN proteins (Schaller et al., 2015). These proteins, as well as several other supporting transport proteins, such as AUX/LAX proteins, help distribute the auxins to the roots where they drive plant growth (Schaller et al., 2015).

In contrast, cytokinins are in charge of division and breaking up the cell. However, they also contribute to shoot growth within plants. Although the hormones are originally synthesized in the plant roots, they are then promptly transferred to the shoot through the xylem (Kang et al., 2017). Several proteins assist in this process; however, the ATP-binding cassette (ABC) transporter ABCG14 has notably been shown to be essential in the cytokinin transportation process to the plant shoot (Kang et al., 2017). The transportation process between the contrasting hormones only further highlights their antagonistic relationship, as auxins are transported from the shoot to the roots while cytokinins are moved in the opposite direction.

However, once the two hormones are delivered to their desired locations, they work together in harmony to ensure the productivity of the plant. To guarantee the effectiveness of the molecular processes driving cytokinin and auxin signaling, proper regulation of the active hormones is necessary. Cytokinins and auxins are able to regulate each other, thus allowing for targeted inhibition based on the concentrations of each hormone. For instance, the antagonistic activity of the complementary hormones allows for the regulation of growth in plant roots and shoots (Kurepa et al., 2019). It was found that at a low to medium concentration, auxins and cytokinins inhibit the signaling of the opposing hormone, with an increase in cytokinin resulting in hindrance of auxin signaling and vice versa (Kurepa et al., 2019). In contrast, at high concentrations, the two hormones were actually found to have an additive effect (Kurepa et al., 2019). Thus, the ratio of the hormonal concentrations plays a large part in plant development, exemplified by increased root development with a high auxin to cytokinin proportion and increased shoot development with a high cytokinin to auxin proportion (Kurepa & Smalle, 2022). Additionally, auxins and cytokinins also specifically work antagonistically in lateral root development (Jing & Strader, 2019). For example, cytokinins interrupt the formation of PIN proteins, which play an important role in auxin transport (Jing & Strader, 2019). Through this, cytokinins are able to regulate when and where root development occurs in the plant (Jing & Strader, 2019). Nevertheless, the two hormones should more accurately be described as complementary rather than contrasting. To be able to properly function, the reciprocal hormones need to coordinate with each other and maintain the balance of auxin and cytokinin homeostasis (Großkinsky & Petrášek, 2019). Therefore, it is evident that the two hormones can both inhibit or promote growth based on certain environmental conditions, exemplifying their complementary and interconnected relationship.

On the molecular level, auxins are recognized by protein receptors (TIR1/AFB). Once the auxin is bound, it acts as a glue for the molecule and forms a connection between the TIR1/AFB and Aux/IAA transcriptional repressors (Fukui & Hayashi, 2018). This then leads to degradation of auxin through Aux/IAA proteins, which frees the auxin response factor (ARF). Once ARFs are released, they are sent to activate or repress those targeted genes that include cell expansion and division (Argueso & Kieber, 2024). Cytokinin has a two-component pathway when it comes to signaling. Specifically, extracellular or cytosolic cytokinins bind histidine-kinase receptors of the CHASE domain (AHK2, AHK3, AHK4) (Argueso & Kieber, 2024). These receptors turn themselves on by adding a phosphate group, such as a histidine amino acid; then, AHP proteins guide the phosphate into the nucleus of the cell. Once the phosphate is inside, it activates proteins called type-B ARR, which activate those genes responding to cytokinins (controlling division or growth of the cell). Lastly, type-A ARR proteins are made to help control the response, often by slowing it down, so that the signal does not keep going forever.

Auxins and cytokinins also play a large role in the plant on the cellular level. For example, auxins were found to correlate with chloroplast development (Tivendale & Millar, 2022). Thus, an increased amount of auxin helps contribute to increased plant growth as the photosynthetic rate of a plant will theoretically be higher (Tivendale & Millar, 2022). Furthermore, mitochondria have been found to play a role in auxin transport and homeostasis, meaning they may be involved in regulating hormone balance despite being an energy-producing organelle (Tivendale & Millar, 2022). Additionally, cytokinins also play a part in chloroplast development by promoting the formation of thylakoid membranes (Cortleven & Schmülling, 2015).

Therefore, on the whole-organism level, auxins and cytokinins are key contributors to plant growth and productivity. By stimulating chloroplast development at the cellular level, the two hormones are able to ensure higher photosynthetic rates that allow for effective plant growth (Tivendale & Millar, 2022). Auxins flow downwards to help elongate cells, drive root formation, and help support those fruit sets. Contrastingly, cytokinins flow upwards to direct cell division, help promote shoot growth laterally, and help allocate nutrients, which helps with leaf aging. Together, auxins and cytokinins create a balance through controlled levels of both; thus, determining how the plant functions and flourishes overall. From branching patterns to the longevity of certain tissues, they drive the whole-organism growth.

Germination

Germination is a significant part of a plant's development, serving as the first step of a lengthy journey of growth. The germination process starts when a seed finds sufficient water, oxygen, and light. The seed absorbs water through the seed coat, activating enzymes and causing embryonic cells to swell. Then, it continues to grow larger and larger until the seed coat splits open and releases the root, followed by the shoot that is composed of the leaves and stem (Bennett, 2021). Inside the seed, the embryo is made up of the embryonic form of roots, stems, leaves, and endosperms–the nutrient store that provides a source of food and energy. From there, in non-endospermic dicots, the cotyledons of the seeds provide the energy through absorption before leaves are fully developed and rely on photosynthesis for the food supply (Bennett, 2021).

When considering the molecular level of germination, several mechanisms take place that allow for the process to function properly. Hormone signaling, such as that of the gibberellic acid (GA) and abscisic acid (ABA) hormones, helps regulate germination based on environmental factors (Han & Yang, 2015). The GA and ABA hormones act similarly to auxins and cytokinins: inducing dormancy or germination depending on the ABA to GA ratio within the cells (Farooq et al., 2022). External cues that indicate appropriate conditions for germination to proceed are recognized by the plant through molecules such as receptor-like kinases (RLKs), which instigate changes in molecular activity that allow germination to proceed (Farooq et al., 2022).

Cellular-level germination is characterized by an increase in metabolism and changes in gene expression, leading to an increase in cell volume and the emergence of the radicle from the seed. When a seed is imbibed, water penetrates the seed to induce cellular activities in the imbibed seed brought about by the end of seed maturation. One of the first and most important events is the growth of the embryonic cells that makes it possible for the radicle to rupture the testa (Bassel et al., 2025). This process is not reliant on cell division but on coordinated modifications in cell size and cell shape in the radicle. The hormone GA is significant at this stage because it activates the transcription of specific growth-promoting genes, promoting cell expansion (Bassel et al., 2025). Cell expansion occurs along the axis of the embryo, which helps to regulate directional growth. Meanwhile, the mitochondria transition to functional organelles that are capable of supporting heterotrophic respiration, which provides the necessary ATP. Once functional and exposed to oxygen, the organelle can generate the ATP necessary to conduct processes of activity associated with early germination (Bassel et al., 2025).

On the whole-organism level, germination marks the beginning of the plant's life cycle. Quick and uniform germination allows them to absorb necessary resources such as sunlight, water, and nutrients. This early advantage allows for stronger root and shoot development, supporting increased plant production, growth, and reproduction. Contrastingly, delayed or uneven germination causes competition for resources, reducing a plant's ability to grow.

Furthermore, Reed, Bradford, and Khanday emphasize the importance of seed vigor in predicting plant development (2022). Seed vigor is a measure of how quickly and reliably seeds germinate under varying conditions; seeds with high vigor are more likely to increase seedling survival, develop deep and strong root systems, and have increased plant biomass. Germinating earlier enhances the plant's ability to compete for resources and maintain steady growth, contributing to higher plant yield. It was found that higher seed vigor in maize led to increased plant height, grain yield, and improved consistency in growth (Reis et al., 2022). These findings demonstrate that germination is an important factor for a plant's development, and the ability to germinate quickly and uniformly gives rise to stronger and more resilient plants.

Future Research Directions

The results of this review demonstrate that the molecular, cellular, and whole-organism levels of these three processes have the potential to aid in novel agricultural techniques. Properly utilizing and applying our knowledge about photosynthesis, auxin and cytokinin signaling, and germination to crop production could support farmers in meeting rising produce demands with the increasing human population. For instance, if cytokinin and auxin concentration ratios could be properly controlled, farmers could make use of this process to promote targeted plant growth (Schaller et al., 2015). Additionally, the optimization of photosynthesis has the potential to increase crop yield (Croce et al., 2024). Furthermore, seed priming could be utilized to initiate germination, therefore promoting higher levels of resilience against long term environmental changes (Granata et al., 2024).

Conclusion

Understanding the biological processes that govern plant growth is becoming increasingly important. Photosynthesis synthesizes the energy required for plant growth and maintenance through the light-dependent reactions and the Calvin cycle in the form of glucose. Auxin and cytokinin signaling promote the proper regulation of root and shoot growth through a reciprocal relationship. Finally, germination is crucial for plant growth and productivity as it initiates the plant's life cycle, setting the stage for the plant to establish roots, absorb nutrients, and ultimately produce food and reproduce. These processes represent the interconnectedness of plant growth as germination is required before photosynthesis can occur, and auxin-cytokinin signaling allows for an increased capacity for photosynthesis through strong plant growth. Previous studies suggest that photosynthesis, germination, and hormone signaling are all well-understood biological processes; however, the applications for these biological processes have yet to be fully developed.

Therefore, the improvement of agricultural techniques through the optimization of biological processes driving plant growth can help fulfill the United Nations Sustainable Development Goals, such as no poverty, zero hunger, and good health and well-being. These processes illustrate the complexities and importance of thoroughly investigating the mechanisms behind plant growth and productivity. Although this study has developed the current understanding of plant growth, it remains important to continue research in this area while also accounting for future developments.

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