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Review on effects of different growth regulators on growth, nutritional status, and yield of wheat

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Abstract
Wheat is a widely cultivated vital cereal crop, that serves as a staple food for a large portion of the world's population. It is grown in diverse agro-climatic conditions and contributes significantly to global food security. It serves as a primary source of energy for millions of people worldwide providing valuable essential nutrients, including carbohydrates, proteins, dietary fibre, vitamins, and minerals. However, its optimal production and productivity faces several major challenges such as climate change, limited water availability, soil degradation, and emerging pests and diseases. Efforts are being made worldwide to address these challenges and improve wheat production and productivity. Growth regulators have been regarded to play a crucial role in wheat crop production by influencing plant growth, development, and responses to environmental conditions. Growth regulators are plant hormones or phytohormones, that are naturally occurring chemical compounds and they regulate various physiological processes in plants. These compounds can be used to enhance plant growth, stimulate root development, regulate flowering and fruiting, and improve stress tolerance. The article provides a critical review on role played by growth regulators in wheat production system.

Keywords: Growth regulators, growth, nutritional status, yield, wheat

Introduction

Definition of growth regulators

Growth regulators, also known as plant hormones or phytohormones, are naturally occurring chemical compounds that regulate various physiological processes in plants. These compounds play a vital role in controlling plant growth, development, and responses to environmental stimuli. Growth regulators can be endogenous (produced within the plant) or exogenous (applied externally to the plant).

Importance of growth regulators in agriculture:

Growth regulators have significant importance in agriculture as they offer a means to manipulate plant growth and development for improved crop production. These compounds can be used to enhance plant growth, stimulate root development, regulate flowering and fruiting, and improve stress tolerance. By manipulating growth regulators, farmers and agronomists can optimize crop yield, quality, and overall performance.

Brief overview of wheat cultivation:

Wheat (*Triticum aestivum*) is a widely cultivated cereal crop that serves as a staple food for a large portion of the world's population. It is grown in diverse agro-climatic conditions and contributes significantly to global food security. Wheat cultivation involves various stages, including land preparation, sowing, crop management, and harvesting. Farmers strive to maximize wheat yield and nutritional quality through the implementation of appropriate agronomic practices.

Current production and productivity scenario for wheat

Wheat is a critical crop globally, and its production and productivity have a direct impact on food security. To meet the increasing demand for wheat, it is crucial to assess the current production and productivity scenario. According to the latest data, wheat production has been steadily increasing in several countries. For example, in 2021, the top wheat-producing countries included China, India, Russia, and the United States (FAO, 2022) [21]. These countries have implemented advanced cultivation practices, improved cultivars, and effective pest and disease management strategies to enhance productivity.

However, challenges such as climate change, limited water availability, soil degradation, and emerging pests and diseases pose threats to wheat production and productivity. Climate change-induced temperature fluctuations, irregular rainfall patterns, and increased frequency of extreme weather events can negatively impact wheat growth and yield (Peng *et al*., 2021) [50]. Additionally, pests like rust diseases and insects, such as aphids and Hessian flies, continue to pose significant challenges to wheat production (Liu *et al*., 2021) [40].

Efforts are being made worldwide to address these challenges and improve wheat production and productivity. Researchers and breeders are developing high-yielding wheat varieties with improved stress tolerance, disease resistance, and nutritional quality (Xu *et al*., 2022) [65]. Integrated crop management practices, including precision farming techniques, optimized nutrient management, and pest control strategies, are being adopted to enhance productivity while minimizing environmental impacts (Kumar *et al*., 2021) [34].

Nutritional importance of wheat

Wheat is a valuable source of essential nutrients, including carbohydrates, proteins, dietary fiber, vitamins, and minerals. It serves as a primary source of energy for millions of people worldwide. Wheat grain comprises various components, including the endosperm, bran, and germ, each contributing to its nutritional composition.

Carbohydrates, mainly in the form of starch, make up the majority of wheat grain, providing energy for human consumption. Wheat proteins, such as gluten, are essential for the formation of dough in bread-making and contribute to the nutritional quality of wheat-based products. The bran and germ of wheat contain dietary fiber, vitamins (such as B vitamins), minerals (such as iron and zinc), and phytochemicals with potential health benefits (Bakht *et al*., 2021) [7]. Consumption of whole wheat products, including whole wheat bread, pasta, and cereals, has been associated with various health benefits. Whole wheat consumption is linked to a reduced risk of cardiovascular diseases, type 2 diabetes, obesity, and certain types of cancer (Aune *et al*., 2021) [5]. The nutritional importance of wheat emphasizes the need to enhance its productivity and quality through improved cultivation practices and breeding efforts.

Growth regulators play a crucial role in agriculture by influencing plant growth, development, and responses to environmental conditions. Wheat, as a vital cereal crop, faces challenges in achieving optimal production and productivity due to various factors. However, ongoing research and advancements in cultivation practices and breeding techniques offer potential solutions to enhance wheat productivity and improve its nutritional importance for global food security.

Types of growth regulators

Plant hormones

Plant hormones, also known as phytohormones, are naturally occurring chemical compounds that regulate various physiological processes in plants. These hormones are produced by plants and act as signaling molecules, coordinating growth, development, and responses to environmental stimuli (Vanneste & Friml, 2009) [61].

1. Auxins

Auxins are a class of plant hormones that play a vital role in regulating plant growth and development. They are involved in various processes, including cell elongation, apical dominance, root development, and tropic responses (Woodward & Bartel, 2005) [64]. The dosage of exogenous auxin application depends on the specific application method and the growth stage of the plant. Proper dosage is crucial to achieve the desired effects without causing negative effects (Peer & Murphy, 2007) [40]. Excessive auxin application can lead to growth inhibition or physiological disorders. The effects of auxins include stimulating cell elongation, promoting root development, enhancing fruit set, and inducing adventitious root formation (Vanneste & Friml, 2009) [61]. Growth retardants, such as synthetic auxin analogs, can be used to control plant height and regulate growth in certain crops (Pacurar *et al*., 2014) [48].

Auxins have significant importance in agriculture as they are used to improve rooting of cuttings, promote lateral root formation, prevent premature fruit drop, and regulate plant height (Li *et al*., 2011) [36]. They are widely applied in horticulture, forestry, and agriculture to enhance crop productivity and quality (Qin *et al*., 2013) [53]. Auxin-based herbicides are also used for weed control. Proper application techniques and timing are essential for maximizing the benefits of auxins in plant growth and development (Prinsen & Van Dongen, 2015) [52].

2. Gibberellins

Gibberellins are plant hormones that regulate various aspects of plant growth and development, including stem elongation, seed germination, flowering, and fruit development (Yamaguchi, 2008) [67]. They are involved in breaking seed dormancy, promoting cell division and elongation, and influencing flowering time and fruit set (Sun & Gubler, 2004) [60]. The dosage of exogenous gibberellin application depends on the specific plant species and growth stage (Hedden & Thomas, 2012) [86].

The effects of gibberellins include stimulating stem elongation, promoting seed germination, inducing flowering, and influencing fruit size and quality (Eriksson *et al*., 2006) [18]. Growth retardants, such as inhibitors of gibberellin biosynthesis or perception, can be used to control excessive stem elongation and promote compact growth (Busov *et al*., 2008) [11].

Gibberellins are of great importance in agriculture as they are used to promote plant growth, increase yield, and improve fruit quality in various crops (Plackett *et al*., 2011) [51]. They have also been utilized to overcome seed dormancy and enhance seed germination in certain plant species (Liu *et al*., 2013) [84].

3. Cytokinins

Cytokinins are plant hormones that regulate cell division, shoot initiation, and the development of chloroplasts. They are involved in the regulation of various plant growth processes, including shoot and root development, nutrient uptake, and delay of senescence (Mok & Mok, 2001) [44]. The dosage of exogenous cytokinin application varies depending on the plant species, tissue, and growth stage. Proper application and timing are crucial for desired effects (Kieber & Schaller, 2010) [32].

The effects of cytokinins include promoting cell division and lateral bud growth, delaying leaf senescence, enhancing nutrient mobilization, and improving stress tolerance

(Argueso *et al*., 2009) [4]. Growth retardants, such as cytokinin antagonists, can be used to control excessive shoot growth and promote branching (Sakakibara, 2006) [56].
Cytokinins have significant importance in agriculture as they are used to enhance shoot formation in tissue culture, stimulate lateral bud growth, delay senescence in harvested crops, and improve fruit quality (Mok & Mok, 2001) [44]. They are also applied in the field to promote nutrient uptake, increase yield, and improve stress tolerance (Kuppu *et al*., 2013) [35].

4. Abscisic Acid
Abscisic acid (ABA) is a plant hormone that plays a crucial role in regulating plant responses to environmental stresses, such as drought, salinity, and cold temperatures. It is involved in seed dormancy, stomatal closure, and inhibition of growth (Cutler *et al*., 2010) [13]. The dosage of exogenous ABA application depends on the specific plant species, developmental stage, and environmental conditions. Careful regulation of ABA levels is essential to balance growth and stress responses (Nambara & Marion-Poll, 2005) [45].
The effects of ABA include promoting seed dormancy, regulating stomatal closure to reduce water loss, inhibiting seed germination under unfavorable conditions, and enhancing stress tolerance (Finkelstein *et al*., 2002) [20]. Growth retardants, such as inhibitors of ABA biosynthesis or perception, can be used to promote seed germination and alleviate growth inhibition under stress conditions (Gonzalez-Guzman *et al*., 2012) [23].
ABA has significant importance in agriculture as it is used to improve crop performance under drought and other abiotic stresses (Bartels & Sunkar, 2005) [8]. It is also involved in regulating fruit ripening and senescence (Zhang *et al*., 2009) [79].

Synthetic Growth Regulators
1. Gibberellin-like substances
Gibberellin-like substances are synthetic compounds that mimic the effects of natural gibberellins. They are designed to regulate plant growth and development, including stem elongation and flowering induction (Rademacher, 2015) [54]. These substances can be applied at specific growth stages and concentrations to achieve desired effects.
Gibberellin-like substances have been used in agriculture to control plant height, promote flowering, and increase fruit size in various crops (Rademacher, 2015) [54]. They are particularly useful in horticulture and ornamental plant production to manipulate plant architecture and enhance aesthetic qualities.

2. Ethylene-releasing compounds
Ethylene-releasing compounds are synthetic substances that release ethylene gas, which is a natural plant hormone involved in fruit ripening, senescence, and various physiological processes (Burg & Burg, 1965) [10]. These compounds are used to control fruit ripening, promote uniform ripening, and enhance shelf life in harvested fruits (Saltveit, 2003) [57].
Ethylene-releasing compounds have practical applications in agriculture and post-harvest management to regulate fruit ripening and extend the storage life of fruits and vegetables (Saltveit, 2003) [57]. They can also be utilized to synchronize flowering in ornamental plants and control plant growth in certain crops.

Effects of Growth Regulators on Wheat Growth
Stem Elongation and Height
Growth regulators have a significant impact on stem elongation and height in wheat plants. The application of growth regulators can either promote or inhibit stem elongation, depending on the specific regulator and its concentration. For example, Gibberellins (GAs) are well-known promoters of stem elongation in many plant species, including wheat (Kobayashi *et al*., 2010) [33]. Exogenous application of GAs can result in increased stem elongation and overall plant height in wheat (Garcia-Hurtado *et al*., 2012) [22]. Conversely, growth retardants, such as synthetic auxin analogs or inhibitors of GA biosynthesis, can be used to control excessive stem elongation and reduce plant height in wheat (Huang *et al*., 2020) [25].

Root Development
Growth regulators also play a crucial role in regulating root development in wheat. Auxins have been shown to promote root growth and branching in various plant species, including wheat (Wang *et al*., 2019) [63]. Exogenous application of auxins can stimulate lateral root formation and enhance overall root system development in wheat plants (Zhang *et al*., 2014) [74]. Additionally, cytokinins have been reported to influence root development by promoting cell division and differentiation in the root meristem (Nguyen *et al*., 2016). These regulators can be applied either through foliar spray or seed treatment to enhance root growth and improve nutrient uptake efficiency in wheat (Miransari, 2017) [43].

Leaf Area Expansion
Growth regulators have a significant impact on leaf area expansion in wheat, which directly influences the plant's photosynthetic capacity and overall growth. Gibberellins, in particular, have been shown to promote leaf expansion in wheat plants (El-Naggar *et al*., 2019) [17]. Exogenous application of GAs can result in increased leaf size and enhanced photosynthetic activity, leading to improved plant productivity (Hussain *et al*., 2019) [26]. Moreover, cytokinins have been reported to regulate leaf development by promoting cell division and leaf initiation (Zhang *et al*., 2013) [78]. Proper application of growth regulators can optimize leaf area expansion and maximize the plant's capacity for photosynthesis.

Tillering and Branching
Tillering, the production of additional shoots from the base of the wheat plant, is a crucial determinant of grain yield. Growth regulators play a key role in regulating tillering and branching in wheat. Gibberellins have been shown to promote tiller development and increase the number of productive tillers in wheat (Liu *et al*., 2019) [85]. Exogenous application of GAs can induce tiller emergence and enhance branching, leading to increased grain yield (Khan *et al*., 2020) [30]. Additionally, cytokinins have been reported to influence tiller development by promoting cell division in the axillary buds (Guo *et al*., 2020) [31]. By strategically applying growth regulators, farmers can manipulate tiller production and optimize grain yield in wheat cultivation.

Effects of Growth Regulators on Nutritional Status of Wheat

Nitrogen Uptake and Utilization

Growth regulators play a significant role in nitrogen uptake and utilization in wheat plants. Nitrogen is an essential nutrient required for various physiological processes, including protein synthesis and overall plant growth. The application of growth regulators can influence nitrogen uptake efficiency and its subsequent utilization. For instance, Gibberellins have been reported to enhance nitrogen uptake and improve nitrogen use efficiency in wheat (Du *et al*., 2021) [14]. They can promote the expression of genes involved in nitrogen transport and assimilation, leading to increased nitrogen uptake and utilization efficiency in wheat plants (Chen *et al*., 2018) [12]. Additionally, cytokinins have been shown to positively affect nitrogen metabolism by regulating the activity of enzymes involved in nitrate reduction and assimilation (Zhao *et al*., 2019) [87]. By enhancing nitrogen uptake and utilization, growth regulators can contribute to improved nitrogen nutrition and overall plant productivity in wheat.

Phosphorus Absorption and Translocation

Phosphorus is another crucial nutrient for wheat growth and development. Growth regulators can influence phosphorus absorption and translocation processes in wheat plants. Auxins have been reported to enhance phosphorus uptake in wheat by promoting root growth and increasing the activity of phosphorus transporters (Niu *et al*., 2018) [47]. Exogenous application of auxins can improve phosphorus acquisition and utilization efficiency in phosphorus-deficient soils (Bai *et al*., 2019) [16]. Moreover, cytokinins have been shown to enhance phosphorus translocation from roots to shoots by regulating the expression of phosphate transporters (Jia *et al*., 2020) [28]. By modulating phosphorus uptake and translocation, growth regulators can enhance phosphorus availability and improve phosphorus use efficiency in wheat plants.

Potassium and Micronutrient Uptake

Growth regulators can also influence the uptake and utilization of potassium and micronutrients in wheat. Potassium is essential for various physiological processes, including enzyme activation and osmoregulation. Gibberellins have been shown to promote potassium uptake and enhance potassium use efficiency in wheat plants (Fang *et al*., 2019) [19]. They can increase the activity of potassium transporters and stimulate potassium uptake by roots (Shi *et al*., 2017) [59]. Additionally, cytokinins have been reported to regulate the uptake and distribution of micronutrients, such as iron and zinc, in wheat plants (Ma *et al*., 2020) [41]. They can enhance the expression of genes involved in micronutrient transport and improve their uptake efficiency. By improving potassium and micronutrient uptake, growth regulators can contribute to balanced nutrient uptake and promote healthy plant growth in wheat.

Chlorophyll Content and Photosynthetic Efficiency

Chlorophyll content and photosynthetic efficiency are crucial determinants of wheat productivity. Growth regulators can influence chlorophyll biosynthesis and photosynthetic activity in wheat plants. Gibberellins have been shown to enhance chlorophyll content and promote chlorophyll synthesis in wheat (Yuan *et al*., 2020) [71]. They can increase the expression of genes involved in chlorophyll biosynthesis and enhance the activity of chlorophyll-related enzymes. Moreover, cytokinins have been reported to enhance photosynthetic efficiency by promoting the activity of photosynthetic enzymes and improving stomatal conductance in wheat (Xu *et al*., 2021) [66]. By enhancing chlorophyll content and photosynthetic efficiency, growth regulators can improve the plant's capacity for photosynthesis and contribute to higher grain yield in wheat.

Effects of Growth Regulators on Wheat Yield

Grain Yield

Growth regulators have a significant impact on wheat grain yield. They can influence various physiological and developmental processes that contribute to grain formation and yield. For example, the application of gibberellins has been shown to increase grain yield in wheat. Research conducted by Zhang *et al*. (2021) [77] demonstrated that exogenous gibberellin treatment resulted in higher grain yield by promoting spikelet fertility and increasing the number of grains per spike. Similarly, auxins have been reported to enhance grain yield in wheat by improving grain filling and increasing the grain weight (Yao *et al*., 2019) [70]. By regulating hormonal signaling pathways and physiological processes, growth regulators can enhance wheat grain yield and contribute to improved agricultural productivity.

Biomass Accumulation

Effective regulation of biomass accumulation is crucial for achieving high wheat yield. Growth regulators play a role in promoting biomass accumulation by influencing various plant growth processes. Research by Liu *et al*. (2020) [39] showed that the application of cytokinins increased biomass production in wheat by enhancing leaf area expansion, photosynthetic activity, and nutrient uptake. Furthermore, gibberellins have been reported to stimulate stem elongation and tiller development, contributing to increased above-ground biomass in wheat plants (Li *et al*., 2021) [38]. By promoting biomass accumulation, growth regulators can provide the necessary resources and energy for grain development, leading to improved wheat yield.

Harvest Index

The harvest index is an important parameter that reflects the partitioning of assimilates between grain yield and vegetative biomass. Growth regulators can influence the harvest index by affecting the allocation of resources within the plant. Studies have shown that the application of growth regulators can increase the harvest index in wheat. For instance, research by Zhang *et al*. (2020) [75] demonstrated that the use of gibberellin-like substances increased the harvest index in wheat by promoting the translocation of assimilates from vegetative tissues to developing grains. Similarly, cytokinins have been reported to improve the harvest index by enhancing grain filling and increasing the proportion of assimilates allocated to the grains (Yang *et al*., 2021) [68-69]. By optimizing resource allocation, growth regulators can improve the harvest index and enhance wheat yield potential.

Grain Quality Parameters

In addition to grain yield, growth regulators can also influence various grain quality parameters in wheat. The application of growth regulators can affect grain size, protein content, starch properties, and other quality attributes. For instance, auxins have been shown to increase grain size and improve grain weight in wheat (Hu *et al*., 2019) [24]. Gibberellins have also been reported to enhance grain quality by promoting grain filling and increasing protein content (Jin *et al*., 2021) [29]. Furthermore, cytokinins have been found to improve starch properties, such as amylose content and gel consistency, thereby enhancing the processing quality of wheat grains (Zhang *et al*., 2022) [72-73-76-80]. By influencing grain quality parameters, growth regulators can enhance the market value and suitability of wheat for various end uses.

Factors Influencing the Response of Wheat to Growth Regulators

Growth Stage

The growth stage of wheat at the time of growth regulator application plays a crucial role in determining the response of the crop. Different growth stages have varying sensitivities and requirements for growth regulators. Research by Yang *et al*. (2021) [68-69] found that applying cytokinins during the tillering stage significantly increased the number of tillers and biomass in wheat. Similarly, auxin application during the reproductive stage was found to enhance grain yield and quality parameters in wheat (Ahmad *et al*., 2022) [1]. Understanding the growth stage-specific responses to growth regulators is important for optimizing their efficacy and avoiding any negative effects on crop development.

Dosage and Application Method

The dosage and application method of growth regulators are critical factors in determining their effectiveness and impact on wheat. The appropriate dosage should be carefully determined based on factors such as the target growth response, crop variety, and environmental conditions. Studies have shown that improper dosage can lead to undesirable effects on wheat growth and yield. For instance, excessive application of gibberellins can result in lodging and reduced grain quality (Li *et al*., 2021) [38]. Additionally, the application method, whether foliar spray, seed treatment, or soil application, can influence the absorption and translocation of growth regulators within the plant. Research by Zhang *et al*. (2022) [72-73-76-80] demonstrated that foliar application of cytokinins at a specific dosage significantly improved grain yield and harvest index in wheat. Proper dosage and application method are essential for achieving desired growth regulator responses without causing any adverse effects.

Environmental Conditions

Environmental conditions, including temperature, light, humidity, and nutrient availability, can affect the response of wheat to growth regulators. Optimal environmental conditions are necessary for the effective uptake, translocation, and utilization of growth regulators by the crop. For example, high temperatures can reduce the efficacy of certain growth regulators and diminish their positive effects on wheat growth and yield (Wang *et al*., 2020) [62]. Additionally, drought stress conditions can influence the response of wheat to growth regulators, and their efficacy may vary depending on the severity and duration of the stress (Beyene *et al*., 2021) [9]. Understanding the interaction between growth regulators and environmental conditions is crucial for maximizing their benefits and minimizing any potential limitations.

Wheat Cultivar

The response of wheat to growth regulators can vary among different cultivars. Some wheat varieties may exhibit higher sensitivity or responsiveness to specific growth regulators compared to others. Research by Zhao *et al*. (2022) [81] found significant differences in the response of different wheat cultivars to auxin treatment in terms of root development and nutrient uptake efficiency. Genetic factors and physiological characteristics of wheat cultivars can influence their ability to respond to growth regulators. Therefore, selecting the appropriate growth regulator and dosage for specific wheat cultivars is important for achieving optimal growth and yield responses.

Application Techniques of Growth Regulators in Wheat Cultivation

Foliar Application

Foliar application involves spraying growth regulators directly onto the leaves of wheat plants. This method offers several advantages, including efficient absorption and quick response due to direct contact with the target tissue. Foliar application of growth regulators has been shown to effectively enhance wheat growth and yield. For instance, research by Akram *et al*. (2021) [2] demonstrated that foliar application of cytokinins significantly increased grain yield and yield components in wheat. Similarly, foliar application of gibberellins has been found to promote stem elongation and improve yield attributes in wheat (Khan *et al*., 2021) [30]. Foliar application is a widely used technique for delivering growth regulators to wheat plants due to its convenience and effectiveness.

Seed Treatment

Seed treatment involves applying growth regulators to the seeds before sowing. This technique allows the growth regulators to be absorbed by the seeds and subsequently transferred to the emerging seedlings. Seed treatment with growth regulators has been shown to improve seed germination, seedling vigor, and early plant growth in wheat. For example, a study by Jafarzadeh *et al*. (2021) [27] found that seed treatment with auxins enhanced the root and shoot growth of wheat seedlings. Additionally, seed treatment with gibberellins has been reported to improve wheat yield and yield components (Ali *et al*., 2020) [3]. Seed treatment offers the advantage of early exposure of the plants to growth regulators, which can have long-lasting effects throughout the growth cycle.

Soil Application

Soil application involves applying growth regulators to the soil around the wheat plants, either by broadcasting or localized placement. This method allows for the uptake and systemic distribution of growth regulators through the root system. Soil application of growth regulators has been found to influence root development, nutrient uptake, and overall plant growth in wheat. For instance, research by Zhang *et al*. (2022) [72-73-76-80] demonstrated that soil application of cytokinins enhanced grain yield and harvest index in wheat. Similarly, soil application of abscisic acid has been reported to improve drought tolerance in wheat plants (Duan *et al*., 2020). Soil application is a practical method for delivering growth regulators, especially for addressing root-related growth and nutrient uptake.

Limitations and Challenges in the Use of Growth Regulators in Wheat Production

Potential Phytotoxicity

One of the limitations of using growth regulators in wheat production is the risk of phytotoxicity, which refers to the adverse effects on plant growth and development. While growth regulators are designed to promote desirable traits in plants, improper application or high concentrations can lead to phytotoxic effects. For example, excessive application of auxins may result in leaf chlorosis and stunted growth in wheat (Malik *et al*., 2021) [42]. Similarly, gibberellin overdose can lead to lodging and reduced grain quality (Zhao *et al*., 2020) [82-83]. To minimize the risk of phytotoxicity, it is crucial to carefully follow recommended dosage and application guidelines.

Environmental Concerns

The use of growth regulators in wheat production raises environmental concerns due to the potential impact on ecosystems and non-target organisms. The runoff or leaching of growth regulators from treated fields can contaminate water bodies and affect aquatic life. Additionally, the persistence of synthetic growth regulators in the environment can pose long-term risks. Therefore, it is important to consider the environmental fate and impact of growth regulators during their application in wheat cultivation. Sustainable practices and adherence to regulations can help mitigate potential environmental risks associated with growth regulator use (Elkelish *et al*., 2021) [16].

Regulatory Constraints

The use of growth regulators in agriculture is subject to regulatory constraints imposed by local authorities. These regulations aim to ensure the safety and efficacy of growth regulator products and protect human health and the environment. Compliance with regulatory requirements regarding product registration, application methods, dosage, and timing is essential for their proper and legal use in wheat production. However, the complex regulatory processes, including registration procedures and restricted availability of certain growth regulators, can pose challenges to their widespread adoption in wheat cultivation (Rodriguez-Diaz *et al*., 2020) [55]. Collaboration between researchers, industry, and regulatory bodies is crucial to address these challenges and facilitate the responsible use of growth regulators in wheat production.

Conclusion

A. Summary of the Effects of Growth Regulators on Wheat Growth, Nutritional Status, and Yield

The use of growth regulators in wheat production has shown significant effects on various aspects of plant growth, nutritional status, and yield. Auxins, such as indole-3-acetic acid (IAA), have been found to promote stem elongation and enhance root development in wheat, leading to increased biomass accumulation and improved crop productivity (Malik *et al*., 2021) [42]. Gibberellins have been shown to stimulate cell division and elongation, resulting in increased plant height, tillering, and enhanced grain yield in wheat (Zhao *et al*., 2020) [82-83]. Cytokinins play a crucial role in regulating leaf area expansion and influencing nitrogen uptake and utilization efficiency in wheat, thereby affecting grain yield and quality (Zhang *et al*., 2022) [72-73-76-80]. Abscisic acid, on the other hand, acts as a growth retardant, inhibiting stem elongation and promoting stress tolerance in wheat plants (Santillán-Hernández *et al*., 2021) [58]. Overall, the application of growth regulators has the potential to optimize wheat growth, improve nutrient uptake and utilization, and increase grain yield.

Implications for Sustainable Wheat Production

The use of growth regulators in wheat production offers several implications for sustainable agriculture. Firstly, the precise application of growth regulators can help optimize plant growth and development, leading to improved resource-use efficiency and reduced inputs such as water and fertilizers. This can contribute to sustainable intensification of wheat production and minimize the environmental impact. Secondly, the manipulation of growth regulators can enhance stress tolerance in wheat, allowing the crop to withstand adverse environmental conditions and reduce yield losses. This is particularly relevant in the face of climate change and increasing abiotic stresses. Lastly, growth regulators can have positive effects on grain quality parameters, including protein content, gluten strength, and nutritional composition, which are essential for meeting the demands of consumers and the food industry.

Future Prospects and Research Directions

While growth regulators have demonstrated their potential in wheat production, there are still several avenues for future research. Firstly, more studies are needed to explore the interactions between growth regulators and other agronomic practices, such as nutrient management and crop protection strategies, to optimize their combined effects on wheat growth and yield. Additionally, there is a need for research on the physiological and molecular mechanisms underlying growth regulator responses in wheat, which can provide insights into their mode of action and potential targets for genetic manipulation. Furthermore, the development of novel growth regulator formulations with improved delivery systems and increased efficacy is an area that warrants further investigation. Lastly, understanding the long-term effects of growth regulator application on soil health, biodiversity, and ecosystem services is crucial to ensure sustainable and environmentally friendly wheat production systems.

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