Plant Archives Vol. 26, Supplement 2, 2026 pp. 1405-1417 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2026.v26.supplement-2.169

ENHANCING WHEAT NUTRITION THROUGH BIOFORTIFICATION AND THE ROLE OF GIBBERELLIC ACID – A COMPREHENSIVE REVIEW

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(Date of Receiving : 17-03-2026; Date of Revision : 23-04-2026; Date of Acceptance : 18-05-2026)

ABSTRACT

Biofortification has become an important approach for addressing micronutrient deficiencies, especially in areas where cereal-based foods form the main part of the daily diet. As one of the world's most important staple crops, wheat offers considerable potential to improve levels of iron, zinc, vitamins and proteins through genetic, agronomic and microbe-based approaches. In recent studies, plant hormones particularly gibberellic acid (GA_3), have been shown to play an important role in nutrient uptake, grain development and the regulation of genes associated with these processes. Gibberellic acid (GA_3) is involved in a range of physiological activities including stem elongation, flowering, grain filling and stress responses and together these processes affect how nutrients are transported to and accumulated in wheat grains. The hormone also regulates a number of genes linked to starch metabolism, nutrient transport and gluten protein formation and often works together with micronutrient fertilization to improve the overall effectiveness of biofortification efforts. Examining hormonal regulation especially the GA_3–DELLA signaling pathway, suggests new ways to combine plant growth regulators with current biofortification approaches. This review summarizes the recent progress made in wheat biofortification and highlights the important role of GA_3 in boosting the nutrient content of grains which can contribute to better human nutrition.

***Keywords* :** Biofortification; Gibberellic acid; Hormonal regulation; Plant growth regulators; Wheat.

Introduction

Living organisms need an adequate and balanced supply of nutrients to support proper growth, development and normal physiological functions (Zhang *et al*., 2024). Out of nearly 90 naturally occurring elements about 17 are considered essential for plants and around 22-25 are considered essential for humans. These nutrients are mainly obtained from air, water and soil where carbon, hydrogen and oxygen come from air and water while remaining mineral nutrients such as nitrogen, phosphorus, potassium, iron and zinc are absorbed from the soil (FAO, 2024). Every elements plays a specialized role in maintaining metabolic balance and securing the nutritional quality of food. A deficiency of even single nutrient can disturb normal biological functions leading to reduced crop productivity and poor health (Hussain *et al*., 2024).

Earlier generations consumed fresh, locally produced foods grown in nutrient- rich soils which naturally met their vitamins and minerals requirements. Agricultural practices were largely organic and soils were fertile and biologically active, ensuring that crops contained an adequate amount of micronutrients necessary for healthy living (Khan *et al*., 2024). However, with the beginning of green revolution period, the focus of agriculture shifted mainly towards enhancing crop yield by adopting high-yield crop varieties along with the application of chemical fertilizers and pesticides although this revolution successfully solved the problem of hunger and increased food production, it gradually led to a decline in the nutritional content of grains due to nutrient mining from soils and over-reliance on chemical inputs (Patel *et al*., 2024). As a result, modern diets often based on polished and processed foods lack adequate micronutrients.

Deficiencies in key micronutrients, including iron and zinc, are recognized as a significant global health problem. Children under five years of age and pregnant or lactating women are particularly susceptible, accounting for approximately 1.5–2 billion affected individuals globally. Countries reliant on cereal-based dietary patterns, especially in Asia and Africa, experience a substantially greater risk (Saeed *et al*., 2024). Even though people now consume enough food to meet their daily energy needs, their diets often lack the essential micronutrients required for good health leading to a condition popularly called hidden hunger- refers to a state of micronutrient deficiency resulting from inadequate intake of essential elements such as iron, zinc, and vitamins (Koc *et al*., 2022). People use vitamin and mineral supplements to help deal with nutrient deficiencies, but the relief they give is only temporary and not the solution to the problem. Therefore, because of the above-mentioned reasons, more emphasis is now being given to the use of sustainable methods such as biofortification. Biofortification is the method of enhancing the quantity of important nutrients in food products during the growing stage, such that the food people regularly consume contains more nutrients, thereby helping to deal with the problem of hidden hunger in a more permanent and viable manner (Avnee *et al*., 2023), (Sheoron *et al*., 2022).

Biofortification, sometimes called biological fortification, is a way to make food crops more nutritious by increasing both the amount and availability of important micronutrients for humans. Crops with higher nutrient content can be developed through traditional breeding, modern biotechnology or better farming practices. In recent years, biofortification has started to be recognized as a practical method to boost micronutrients in staple foods (Sow *et al*., 2021). Studies show that regularly eating biofortified crops can improve micronutrient intake and have positive effects on human health (Bouis *et al*., 2021). One of the main approach agronomic biofortification focuses on giving plants nutrients directly either through soil treatment or spraying mineral fertilizers on leaves. This also involves managing the soil and crops in ways that help minerals move more easily in the soil so that plant roots can take them up better. Because of its relative simplicity, low cost and ease of implementation, agronomic biofortification is widely regarded as one of the most economical and effective strategies for addressing mineral deficiencies in the human diet (Szerement *et al*., 2022)

In major cereal crops including wheat, rice and maize, biofortification strategies have been focused primarily on Fe and Zn because of their critical role in human health and their naturally low concentration in grains (Naveed *et al*., 2020). Breeding efforts under the HarvestPlus initiative have produced biofortified varieties with improved micronutrient levels. Agronomic biofortification with iron and zinc applied either to the soil or foliage has been found to effectively raise nutrient concentrations in grains in field trials.

Nutritional importance of wheat

Wheat *(Triticum aestivum* L.) is one of the most important cereal crops belonging to *Poaceae* family and a staple food crop of the world. Wheat is also called as “King of Cereals” because of its high nutritional quality, wide adaptability, huge global cultivation area, high yield potential and excellent storage properties (Chaudhary *et al*., 2024). It serves as an important source of energy, nutrients and fiber in the human diet (Khalid *et al*., 2023). It is an essential part of human nutrition due to both its comprehensive nutrient composition and its popularity across the globe (Singh *et al*., 2023).

1. **Source of Energy**: Wheat is a significant source of complex carbohydrates, mostly composed of starch which supply long-lasting energy to the body. Carbohydrates make up about 70–75% of the grain’s dry weight, that is why it serves as a major source of energy in the human diet (Sunic *et al*., 2024).
2. **Protein Content**: Wheat provides around 10–15% protein, including gluten which is responsible for the elasticity and strength of dough. Proteins play a vital role in developing enzymes, which propel different biological processes, facilitate tissue repair and promote growth (Safdar *et al*., 2023).
3. **Dietary Fiber**: Whole wheat along with its bran, offers a healthy dose of dietary fiber. The fiber content ensures smooth functioning of the digestive system, regulates bowel movements, controls cholesterol levels and maintains blood sugar levels (Saini *et al*., 2023).
4. **Vitamins:** Wheat is a good source of B-complex vitamins, i.e., thiamine (B1), riboflavin (B2), niacin (B3) and folic acid (B9). These vitamins play a vital role in energy production, proper functioning of the nervous system and hemoglobin synthesis in red blood cells (Khalid *et al*., 2023).
5. **Minerals:** Wheat also offers essential minerals like iron, magnesium, phosphorus, zinc and selenium.

These minerals help build and maintain healthy bones, a robust immune system and proper oxygen circulation in the blood (Meenu *et al.*, 2025).

6. **Antioxidants and Phytochemicals:** Whole wheat comprises a number of different compounds, i.e., phenolic acids, flavonoids, and lignans which helps to protect against diseases by acting as antioxidants in the body (Kobayashi *et al.*, 2025).
7. **Low Fat Content:** Wheat contains a low amount of fat, i.e., only 1.5-2%, which makes it a healthy addition to a balanced diet and a vital component in weight management (Khalid *et al.*, 2023).

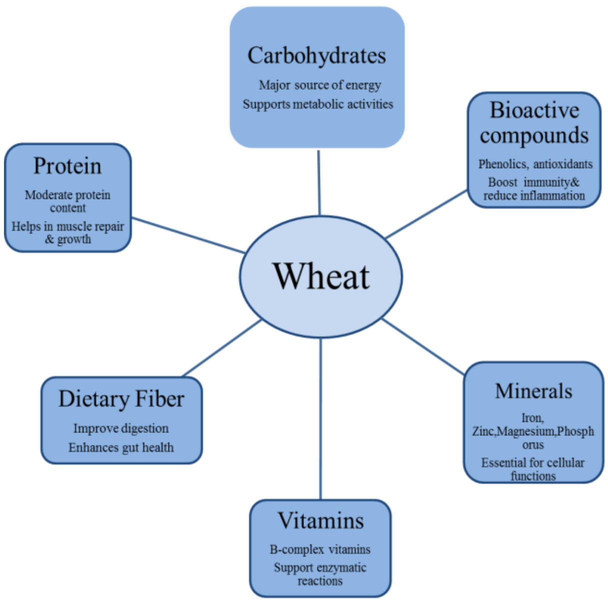

Fig. 1 : Nutritional importance of wheat

Concept and significance of Biofortification

Biofortification is a way to make food crops more nutritious by increasing the amount of essential vitamins and minerals in the parts of the plant we eat. This may be done through conventional breeding, improved agricultural practices, or the use of modern bio-technology techniques (Singh *et al.*, 2016). Biofortification is distinct from conventional industrial fortification in that, rather than adding nutrients during food processing, nutrients are enriched in the food during its natural growth cycle in the field. The main objective of biofortification is to enhance the natural health benefits in food, especially in staple foods, by adding essential nutrients required for health, such as iron, zinc, vitamin A, iodine and protein (Wakeel *et al.*, 2018). To illustrate, biofortified wheat varieties such as Zinc Shakti and WB02 have been developed with high levels of zinc and iron, while Golden Rice is enriched with vitamin A, and beans and pearl millet contain high levels of iron compared to conventional types (Kumar *et al.*, 2019).

The main goal of biofortification is to control the problem of hidden hunger that results from people failing to obtain adequate vitamins and minerals from the food that they eat on a daily basis. This is a common problem that is experienced in most developing countries, where people mostly rely on food such as rice, wheat and maize. This food is essential for the purpose of filling the stomach but it is usually not enough for the body (Zulfiqar *et al.*, 2024).

Significance of Biofortification

1. **Prevents Hidden Hunger and Nutrient Deficiencies:** It helps to reduce health problems resulting from inadequate intake of nutrients such as iron, leading to anemia, zinc resulting in stunted growth and vitamin A, resulting in vision problems (Ofori *et al.*, 2022).
2. **An Easy and Lasting Way for Farmers:** Once the farmers have biofortified crops, they will continue planting these crops year in and year out without incurring any additional cost, thereby helping communities fight malnutrition over time (Sharma *et al.*, 2024).
3. **Supports Better Health:** Consumption of nutrient-dense crops regularly can maintain a healthy immune system, aid in brain development in children and reduce the risk of health complications in adults (Ashraf *et al.*, 2025).
4. **Makes Everyday Food Healthier:** This improves the quality of diet by making the basic crops that people are already eating healthier, without requiring them to change anything about their eating habits (Bhardwaj *et al.*, 2022).
5. **Good for the Environment:** Since biofortified crops are naturally enriched with additional nutrients, there is no requirement for any artificial fortification or supplements, which makes them environmentally friendly (Arora *et al.*, 2025).
6. **Benefits Health and Farming Initiatives:** This method is useful in helping global initiatives such as the UN's Zero Hunger initiative, which focuses on improving crop nutrition and increasing food production (Wani *et al.*, 2022).

Approaches of Biofortification in wheat

Biofortification can be carried out through various means by employing conventional breeding techniques, simple farming techniques and genetic engineering to enhance nutritional content.

1. **Conventional Breeding:** The most common and inexpensive method of improving wheat is conventional breeding. This involves cross-

breeding wheat varieties that are naturally high in nutrients and selecting the best plants over time. The objective of this method is to develop wheat that not only thrives but also has more nutrients. These plants are then subjected to various environmental conditions to ensure that they perform optimally (Wani *et al*., 2022). One such example of this method includes the development of the Gpc-B1 gene found in wild wheat, which increases the amount of protein and zinc and iron content in wheat (Krishnappa *et al*., 2022).

2. **Molecular and Genetic Approaches:** Wheat can be made to contain more iron, zinc and protein by working with its natural genes. Modern tools are used to identify the genes that control how nutrients are absorbed, moved and stored in the plant. Techniques like QTL mapping, marker-assisted selection, and genome-wide studies help find the genes responsible for higher iron and zinc levels. Making certain genes, such as NAS, ZIP, YSL and Ferritin more active allows the plant to take in more nutrients and store them in the grains. Tools like CRISPR/Cas9 can change these genes and even reduce substances like phytic acid that make nutrients harder for the body to absorb. Combined with good farming practices, these methods can produce wheat that is richer in nutrients without lowering crop yields (Kartseva *et al*., 2023).

3. **Agronomic biofortification**: Agronomic biofortification improves the nutrient content of crops by using better soil care and farming methods instead of changing the plant's genes (Tiwari *et al*., 2026) It's main aim is to increase the availability, uptake and movement of important nutrients like zinc, iron, selenium and iodine from the soil into the parts of the crop that people eat (Toor *et al*., 2021). This can be done in several ways such as adding nutrients directly to the soil, spraying them on the leaves, treating seeds before planting or using fertilizers that are enriched with minerals (Aslam *et al*., 2023). These practices help crops to take in and move nutrients more efficiently resulting in food with higher nutritional value (Dhaliwal *et al*., 2022).

Agronomic biofortification is employed to control hidden hunger that occurs when people are unable to get adequate vitamins and minerals. This mostly occurs in societies that depend on cereal-based diets (Chaudhary *et al*., 2025). The main techniques employed are:

1. **Soil Application**: Small amounts of nutrients such as zinc sulfate or iron sulfate are added to the soil so that the roots of the plant can absorb them more easily (Mannan *et al* ., 2022).

2. **Foliar application** : Nutrient solutions are applied directly to the leaves and the plants will absorb them quickly and transport them to the grains (Basvantrao *et al*., 2024).

3. **Preparation of Seeds with Nutrients**: In this method, the seeds are first soaked in nutrient solutions before they are planted. This ensures proper germination of the seeds and development of strong roots and shoots (Bhatia *et al*., 2022).

4. **Enriched Fertilizers**: Using nutrient-enriched fertilizers, like zinc-enriched urea or selenium-enriched NPK, is a simple solution for correcting several nutrient deficiencies simultaneously (Chaudhary *et al*., 2025).

The benefits of agronomic biofortification over other methods of biofortification include that it is an inexpensive method, easy to do and is best for small-scale farmers (Huey *et al*., 2025). In addition, agronomic biofortification is useful for the rapid enhancement of nutrient content of crops, while traditional breeding methods take a long time (Ullah *et al*., 2025). This method is also useful for the simultaneous enhancement of the nutritional value of crops, allowing them to grow better, maintain healthy soils and strengthen crops (Chaudhary *et al*., 2025). The application of fertilizers that are rich in micronutrients allows crops to take up the required nutrients efficiently and cope with stress. This method of biofortification is easy to do along with the application of fertilizers (Gautam *et al*., 2025).

Role of Plant Growth Regulators in improving nutrient uptake

Plant Growth Regulators (PGRs) are of great importance in the uptake, transport, and utilization of nutrients by plants (Roychoudhary *et al*., 2022). These are naturally occurring substances like auxins, gibberellins, cytokinins, abscisic acid and ethylene that are effective in very small quantities. They are effective in the growth of roots, cell activity and nutrient transport of plants, even in small quantities.

Auxins assist roots to develop and elongate, and this causes the development of side roots, which enhances the surface of the roots and enables them to acquire more nutrients (Panozzo *et al*., 2025). Cytokinins assist in the movement of nutrients in the plant and slow down the aging of the leaves to ensure proper utilization of the nutrients (Velandia *et al*., 2024). Gibberellins assist in the division and elongation of cells and this causes the development of stronger roots that are able to acquire nutrients deeper in the soil (Khan *et al.*, 2025). Abscisic acid (ABA) assists in maintaining the right balance of ions in the plants by ensuring that the roots and the stomata are in the right state, and ethylene assists in the development of root hairs, which enhances the acquisition of nutrients by the plants (Zhumanova *et al*., 2024).

In addition, plant growth regulators do not only influence the development of roots but also influence enzymes' activities and the movement of substances that pass through the membranes of cells, which is essential for nutrient absorption and translocation (Sun *et al*., 2022). For example, plant growth regulators such as auxins and cytokinins enhance the activity of proton pumps on the membranes of cells of the roots thus enabling the plant to absorb essential nutrients such as nitrogen, phosphorus and potassium (Madhupriya *et al*., 2026).

Studies have also indicated that the application of plant growth regulators enhances the utilization of nutrients by the plant and its ability to absorb essential micronutrients such as iron, zinc and manganese from soils that are poor in nutrients or under stressful conditions (Sun *et al*., 2022).

Gibberellic acid (GA_3) as a key growth regulator in wheat nutrition

Gibberellic acid (GA_3) is an important growth regulator for improving growth, productivity, and nutrient content in wheat (Shahzad *et al*., 2024). It facilitates growth, division, and development of cells properly, which results in stronger roots and shoots and easy nutrient uptake by the plants from the soil (Kumudini *et al*., 2019). GA_3 also enhances the growth of roots and their surface area, which helps the plants to take up essential macro and micronutrients, thereby finding its place in wheat biofortification (Masood *et al*., 2016).

Gibberellic acid (GA_3) also influences the movement of nutrients in the plants by promoting metabolic activities like enzyme synthesis and enhancing photosynthesis. This will help to mobilize micronutrients like iron, zinc and manganese to the developing grains, thereby enhancing their nutrient content (Martins *et al*., 2023). Gibberellic acid treatment of wheat grains in the form of a foliar spray or seed treatment will help to improve grain yield and growth, and also the micronutrient content of wheat kernels (Rietra *et al*., 2017).

Gibberellic acid (GA_3) boosts the activity of key enzymes like nitrate reductase and carbonic anhydrase, which are required for nutrient metabolism and utilization in plants (Nasim *et al*., 2025). This ensures efficient utilization of nutrients and their translocation to grains (Faizan *et al*., 2026). Application of GA_3 along with other agronomic biofortification approaches like application of micronutrient fertilizers will enhance nutrient absorption and their accumulation in plant parts destined for consumption (Ayub *et al*., 2021).

Thus, Gibberellic acid (GA_3) is significant in the biofortification of wheat, as it aids in the growth of the plant and also enhances the nutritional content of the grains (Gautam *et al*., 2025). The application of GA_3 in the biofortification of wheat enhances the physiological functions, nutrient uptake, and movement in the plants, thereby increasing the levels of nutrients in the parts of the wheat that are harvested (Shah *et al*., 2023). It helps in increasing the levels of nutrients in the grains, thereby increasing crop yield, which in turn helps in keeping the levels of deficiencies low (Rademacher *et al*., 2016).

Table 1 : Role of Gibberellic acid (GA_3) in plants

S. No.	Role of GA_3	Process/Mechanism	Effect on Plant	Reference
1	Stem elongation	Enhanced cell division and cell elongation	Increased internode length and plant height	(Anwar *et al*., 2023)
2	Seed germination	Induces α-amylase & other hydrolytic enzymes	Breaks dormancy and promotes uniform germination	(Bhatla *et al*., 2023)
3	Flowering induction	Regulates floral meristem transition	Promotes flowering in long-day plants	(Ramazan *et al*., 2026)
4	Fruit set & growth	Stimulates cell expansion and hormonal balance	Increases fruit size and reduces fruit drop	(Luo *et al* ., 2024)
5	Delay of senescence	Slows chlorophyll degradation	Leaves stay green longer,higher	(Amri *et al*.,

		pathways	photosynthesis	2016)
6	Breaks bud dormancy	Activates metabolic processes in buds	Bud sprouting and early growth	(Hasna *et al*., 2024)
7	Stress tolerance	Modulates antioxidant enzymes & osmolytes	Better tolerance to drought, heat, salinity	(Ullah *et al*., 2025)
8	Enzyme activation	Increases amylase, proteases, expansins	Faster seedling growth and metabolism	(Bhatla *et al*.,2023)
9	Bolting	Promotes rapid elongation of stem in rosettes	Early transition to reproductive phase	(Ramazan *et al*., 2026)
10	Gene expression regulation	Induces GA-responsive genes	Overall growth enhancement	(Thapa *et al*., 2024)

Nature and mode of action of gibberellic acid (GA_3)

Belonging to the gibberellin group, gibberellic acid (GA_3) is a major plant growth regulator consisting of naturally occurring diterpenoid acids, which are vital in managing several developmental processes in higher plants (Elshafey *et al*., 2018), (Kalra *et al*., 2018). GA_3 was first isolated from the fungus *Giberella fujikuroi*, which was found to cause the "bakanae" or foolish seedling disease in rice, characterized by excessive elongation of the plant (Tanimoto *et al*., 2025). Later, it was discovered that gibberellins are also naturally synthesized in plant themselves (Pandey *et al*., 2025).

GA_3 is mainly produced in the plant's rapidly growing regions such as the tips of roots, emerging leaves and maturing seeds (Thapa *et al*., 2024). Chemically, GA_3 is a crystalline, weakly acidic and non-volatile compound that is soluble in organic solvents like ethanol and slightly soluble in water (Castro *et al*., 2022). It is stable in dry form but can be degraded under strong acidic or alkaline conditions (Dai *et al*., 2025).

Gibberellic acid (GA_3) is a growth hormone which regulates a number of physiological processes in the plant body. It includes stem elongation, seed germination, breaking seed dormancy, activating enzymes, flower formation and fruit development (Luo *et al*., 2024). GA_3 helps in the elongation and expansion of the plant body to grow taller. That is the reason GA_3 is called the stem elongation hormone (De Nittis *et al*., 2025).

The Way Gibberellic Acid (GA_3) Works in Plants

1. Regulation of gene expression

Gibberellic acid (GA_3) is involved in the control of growth in plants by regulating gene expression. It triggers the expression of specific mRNA in the nucleus, which is then used for the synthesis of required enzymes for growth (Thapa *et al*., 2024). In the process of germination in wheat grains, GA_3 triggers genes that produce α-amylase in the aleurone layer, which is then used for the breakdown of food reserves, thereby linking the action of the hormone with the metabolism of the plants (Ahmad *et al*., 2025).

2. Breaking of dormancy

GA_3 is commonly used due to its capacity to break seed and bud dormancy. In some plants, dormancy is usually due to some chemical inhibitors or because the seed and buds are metabolically inactive. GA_3 aids the plant to break these barriers through increased metabolic activity and assisting the plant to produce enzymes to break down these inhibitors to aid in germination. It also makes the seed coat soft to allow easy root emergence. This property is widely used in agriculture and horticulture to encourage uniform seed germination and to help dormant buds sprout especially in crops like potatoes and sugarcane (Kroupin *et al*., 2023).

3. Activation of enzymes during seed Germination

GA_3 plays a vital role during the process of seed germination, as it initiates the chemistry that gets things moving. In cereals such as wheat and barley, GA_3 synthesized in the embryo triggers the production of hydrolytic enzymes such as α-amylase, proteases, and lipases in the aleurone layer (Bhatla *et al*., 2023). These enzymes convert the stored food materials in the endosperm mainly starch, proteins and lipids into simpler and soluble forms such as sugars and amino acids. These compounds are then transported to the growing embryo to provide the energy and nutrients required for germination. Without GA_3, these enzymes are not synthesized and seed germination remains incomplete (Kroupin *et al*., 2023).

4. Promotion of cell elongation and division

One of the main roles of GA_3 is to stimulate cell elongation and division, especially in stems and internodes (Anwar *et al*., 2023). GA_3 also aids in relieving the rigidity of the plant cell walls through an increase in the production of enzymes, such as expansins and hydrolases, which make the walls more elastic. This allows the plant cells to easily take up more water and grow rapidly (Mijdi *et al*., 2024). It also promotes plant cell division, especially in meristematic tissues, which encourages plant cell development (Sabir *et al*., 2025). This means that plants treated with GA_3 tend to grow taller, with longer internodes, hence more vigorous (Farooq *et al*., 2022).

5. Induction of bolting and flowering

GA_3 application may lead to bolting, which is characterized by a sudden increase in internodes, thereby creating space for the flowering stalk to come out (Ramazan *et al*., 2026). It can also stimulate flowering in long-day plants even when they are subjected to short days, thus bypassing the process of day length requirement (Nadeem *et al*., 2025). In this way, GA_3 aids plants in their transition from the vegetative stage to the reproductive stage to ensure that flowering occurs at appropriate times and ensures reproductive success (Ritonga *et al*., 2023).

Role of GA_3 in the Development of Wheat Plants

Gibberellic acid is an important hormone that influences the development and growth of wheat plants in several ways (Tao *et al*., 2024). The important functions of gibberellic acid in wheat plants are to increase the growth of the stem, promote the growth of roots and shoots, increase the size of leaves and facilitate the development of seeds (Ramaden *et al*., 2024).

1. **Accelerated Seed Germination:** In wheat plants, the role of GA_3 is to trigger the production of hydrolytic enzymes such as α-amylase by the aleurone layer which split the starch into glucose providing the energy needed by the germinating seeds (Roy *et al*., 2022).
2. **Regulation of Metabolism in Plants:** The role of GA_3 in wheat plants is to regulate the production of hydrolytic and oxidative enzymes which are important in the utilization and transport of nutrients to different parts of the plant (Mathpal *et al*., 2022).
3. **Development of Root System:** GA_3 triggers root formation and elongation resulting in a greater root surface area and density (Ali *et al*., 2024). The root network helps in soaking up more water and nutrients from the soil (Datta *et al*., 2023).
4. **Efficient movement of nutrients:** GA_3 helps in transporting nutrients and food from the leaves to the seeds, thus increasing crop yields (Mathpal *et al*., 2022) .
5. **Growth of stems and leaves:** GA_3 activates enzymes to break down cell walls, thus increasing the rate of cell growth to elongate stems and leaves to produce food crops (Ramadan *et al*., 2024), (Robil *et al*., 2025).

Ways through which the growth responses induced by GA_3 increases the uptake of nutrients

GA_3 induces several changes in the plant that enhance its nutrient uptake. They are as follows:

- **Increased root development:** The higher the root elongation and root branching, the more the roots will interact with the soil particles and therefore the higher the efficiency of nutrient uptake such as nitrogen, phosphorus, zinc and iron (Zarea *et al*., 2025).
- **Higher metabolic activity:** GA_3 increases the activity of enzymes involved in ion transport and nutrient assimilation, helping the plant use nutrients more efficiently (Shaddad *et al*., 2013).
- **Increased photosynthetic efficiency:** GA_3 increases the efficiency of photosynthesis through enhanced leaf size, thereby increasing the production of chlorophyll which in turn increases the rate of photosynthesis to give the plant more energy to transport nutrients (Amri *et al*., 2016).
- **Increased transpiration stream:** The taller plants with larger leaves have increased transpiration which results in an increased pull of the xylem, thus facilitating the transport of mineral nutrients to different parts of the plant (Islam *et al*., 2014).

Role of GA_3 in enrichment of Grains

Gibberellic acid is a major regulator in improving the nutritional quality and quantity of wheat grains by regulating the physiological and biochemical processes involved in nutrient transport, accumulation and storage (Ajayo *et al*., 2026). The use of GA_3 is effective in improving the transport of major minerals such as iron (Fe) and zinc (Zn) from the vegetative part of the plant to the developing grains, thus making it an effective biofortification agent (Pandey *et al*., 2018).

GA_3 enhances the sink potential of developing grains by promoting cell division, elongation, and the activity of major enzymes in reproductive organs (Tripathi *et al*., 2025). This leads to a greater filling of grains, which means a greater accumulation of carbohydrates, proteins and other nutrients (Zarea *et al*., 2025). GA_3 also increases the phloem loading and the movement of assimilates, thus providing a constant supply of nutrients and assimilates to the grains during their formation. GA_3 not only enhances the movement of nutrients, but it also increases the activity of enzymes that facilitate the assimilation of nutrients.This enzymatic regulation is critical in enhancing the concentration of iron, zinc and other major micronutrients that are vital in human health (Tripathi *et al*., 2025).

GA_3 is normally applied in combination with other plant hormones such as auxins and cytokinins to ensure that there is a balance between vegetative growth and reproductive growth. The interaction between GA_3 and other plant hormones enables the plant to allocate nutrients in a more efficient manner, hence increasing yields and improving grain quality (Kumar *et al*., 2025). The use of GA_3 in improving the nutritional quality of grains is directly related to its ability to improve nutrient uptake, mobilization and accumulation in developing grains (Sharma *et al*., 2025). By ensuring efficient nutrient transport and metabolism, GA_3 not only improves crop yields but also improves the nutritional quality of grains making it a very important component in plants to biofortify wheat.

Role of GA_3 in Enhancing Nutrient Uptake and Biofortification

Gibberellic acid is significant for enhancing nutrient uptake and biofortification in plants especially in cereal crops such as wheat (Ullah *et al*., 2025). It acts as a growth-promoting hormone that regulates various physiological, biochemical and molecular mechanisms that work together for improving the uptake, transport and storage of nutrients in plant tissues and developing grains (Kumar *et al*., 2025).

Impact on Plant Nutrient Absorption

GA_3 has a positive effect on nutrient uptake mainly because of its ability to trigger root growth and activity. GA_3 triggers root growth, root branching and root hair extension, hence increasing the total root surface area in contact with the soil (Pandey *et al*., 2018). The increased root surface area allows the plant to access a larger volume of soil and a larger quantity of vital nutrients such as nitrogen (N), phosphorus (P), potassium (K), zinc (Zn), and iron (Fe). Moreover, GA_3 regulates the processes involved in nutrient transport in the plant (Tripathi *et al*., 2025). GA_3 increases xylem loading and transpiration stream, hence ensuring the efficient transport of minerals from the roots to the shoots. GA_3 increases enzyme activation and biosynthesis of membrane transport proteins, which are involved in ion uptake and nutrient assimilation. GA_3 triggers leaf expansion and chlorophyll increase, hence increasing photosynthesis efficiency, which provides energy for the active transport and assimilation of nutrients (Zarea *et al*., 2025). Plants treated with GA_3 exhibit enhanced nutrient uptake, growth, and physiological processes (Thapa *et al*., 2024).

Influence on Biofortification

In addition to this, GA_3 has a crucial role to play in biofortification, a process aimed at increasing the content of vital micronutrients in plant parts, such as grains, that are consumed as food. GA_3 facilitates the transport of micronutrients, including iron (Fe) and zinc (Zn), from plant vegetative parts to developing grains during the grain-filling stage (Castron *et al*., 2022). As a result, a continuous supply of nutrients and assimilates to developing plant parts is ensured. GA_3 also plays a crucial role in enhancing the sink capacity of developing grains. It does this by stimulating cell division, elongation and enzyme activity, thus enhancing nutrient deposition in developing grains (Kumar *et al*., 2025). Consequently, this leads to a significant improvement in grain quality, as well as an increase in iron, zinc, and other vital micronutrient contents. At a molecular level, GA_3 controls nutrient metabolism and storage-related genes, thus promoting the formation of proteins and enzymes that convert micronutrients into forms that are easily absorbed (Sharma *et al*., 2025). In this way, there is an improvement in the quality of grains, as well as an increase in iron, zinc and other vital micronutrient contents. Additionally GA_3, in combination with other plant hormones such as auxins and cytokinins, ensures a balance in nutrient distribution between plant vegetative and reproductive parts, thus enhancing both yield and quality (Kamaral *et al*., 2025).

Generally, the effect of GA_3 on the plant involves the regulation of the growth of the plant as well as the improvement of the uptake of the nutrients and the biofortification of the nutrients (Ullah *et al*., 2025). The use of GA_3, enhances the uptake of the nutrients by the plant and the nutrients in the grains produced by the same plant. GA_3 therefore, is of critical importance in modern agriculture as it enhances the yield of the food crops and the nutrients in the grains produced by the same plant (Thapa *et al*., 2024).

Major Challenges and Key Limitations

Although the GA_3-mediated biofortification of wheat has shown promising potential, a number of challenges have been identified as limiting factors in the effective utilization of the technology. The first challenge is the differential response of different varieties of wheat and the environment to the application of GA_3. The optimal amount of GA_3

required may vary depending on the developmental stage of the plant, thus making it difficult to draw guidelines on the effective utilization of the technology. The chances of undesirable side effects may also arise if the amount of GA_3 is in excess. The interaction of GA_3 with other plant hormones and nutrients in the soil may also be complex, thus making it difficult to obtain the desired results. The cost of the process of externally applying GA_3 may also be a limiting factor in the effective utilization of the technology. The molecular mechanisms by which GA_3 influences the movement of micronutrients in the grains of the plant are still poorly understood. The effect of different environmental factors, which may include the type of soil, moisture content, and temperature changes, may be complex in influencing the utilization of GA_3 in the effective biofortification of the plant. However, a better understanding of the interaction of GA_3 with different environmental factors is required to obtain the desired results in the utilization of the technology.

Future prospects

Future studies on GA_3-induced biofortification in wheat have great potential for improving both yield and nutritional quality. Recent advances in the study of plant physiology and molecular biology can provide an explanation for the mechanisms of action of GA_3-induced nutrient uptake, transport, and accumulation in wheat grains. The use of GA_3 technology with conventional breeding techniques and other emerging biotechnologies can provide an impetus to the enrichment of wheat grains with essential micronutrients. The optimization of the rate and timing of GA_3 technology under different environmental conditions will be important to ensure the reproducibility of results under practical conditions. The combination of GA_3 technology with other nutrient management strategies and plant growth regulators will also be beneficial in enhancing the efficiency of this technology. The development of cost-effective and eco-friendly technology for GA_3 will also be beneficial for making this technology viable for practical use. In conclusion, it can be said that the use of GA_3 technology for agronomic biofortification is a viable and sustainable approach to overcome the problem of hunger and to produce nutrient-rich wheat grains for future generations.

Conclusion

Biofortification has been recognized as an effective and sustainable method for enhancing the nutritional quality of major crops such as wheat. Gibberellic acid (GA_3) is an important ingredient of different methods aimed at accelerating plant growth, allowing plants to uptake higher quantities of nutrients and increasing the ability of grains to hold higher quantities of nutrients.GA_3 helps in root strengthening, micronutrient transport and grain filling which are collectively responsible for improving the nutritional value of wheat. However, changes in the environment and the different varieties of wheat may pose some challenges but the reward of research on GA_3, in combination with the current techniques is enormous. In essence, the GA_3 biofortification method is a promising technique for the production of more nutritious wheat which in turn will improve food security and nutritional security.

Acknowledgements

The authors gratefully acknowledge the valuable support and encouragement provided by HoD (Agronomy section), Director, Faculty of Agriculture MM(DU) Mullana and University Administration.

Authors' contributions

SK: literature collection and manuscript drafting; **AB**: study conceptualization, methodological design and manuscript editing; **AS**: study conceptualization, methodological design and manuscript editing; **R**: literature collection and information extraction; **S**: literature collection and manuscript revision. All authors have read and agreed to the published version of the manuscript

Compliance with ethical standards

- **Conflict of interest:** Authors do not have any conflict of interest to declare.
- **Ethical issues:** None

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