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Secrets Beyond the Basics in Plant Nutrition: The Potential of Titanium, Zirconium, Chromium and Iodine:Mini Review

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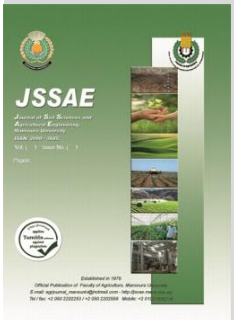

ABSTRACT

In the quest to enhance plant nutrition, this review examines the potential roles of titanium (Ti), zirconium (Zr), chromium (Cr), and iodine (I) in plant growth and development. While traditional plant nutrition focuses on essential macro and micronutrients like nitrogen, phosphorus, and potassium, emerging research suggests that non-essential elements may offer significant benefits. Titanium, though non-essential, has shown promise in improving plant growth and photosynthetic efficiency by stimulating enzymatic activities and enhancing nutrient uptake. Zirconium, often overlooked, is suggested to benefit root development and overall plant health, though research is still in its early stages. Chromium, known for its toxicity at high levels, may enhance nutrient uptake at trace levels, particularly iron and phosphorus, contributing to stress tolerance. Iodine, traditionally not vital for plants, has been observed to support physiological processes and increase resistance to biotic and abiotic stresses, particularly in iodine-deficient soils. Including these elements in plant nutrition could revolutionize agricultural practices, offering new tools for sustainable and efficient food production. However, careful management is essential to avoid toxicity and environmental impact. Further research is needed to understand these elements' specific mechanisms and establish safe guidelines for their use. Overall, exploring non-essential elements like titanium, zirconium, chromium, and iodine offers a promising frontier in agricultural science, potentially enhancing crop resilience and productivity in the face of global challenges.

Keywords: Titanium, Zirconium, Chromium, Iodine

INTRODUCTION

Plant nutrition is a cornerstone of agricultural science, traditionally focused on a well-defined set of essential macro and micronutrients critical for plant growth and development. These essential nutrients, including nitrogen (N), phosphorus (P), potassium (K) and various trace elements, have been the subject of extensive research and application in farming practices worldwide (Elbasiouny *et al.* 2022). However, as the global agricultural landscape faces increasing challenges such as soil degradation, climate change, and the need for sustainable food production, there is growing interest in exploring the roles of less conventional elements from the periodic table in plant nutrition (El-Ghamry *et al.* 2024b).

This review delves into the potential nutritional benefits of four such elements: titanium (Ti), zirconium (Zr), chromium (Cr), and iodine (I). Although not traditionally considered essential for plant growth, these elements may offer significant advantages when it comes to enhancing plant health, increasing resilience to environmental stressors, and potentially boosting crop yields (Ghazi *et al.* 2021). By expanding the scope of plant nutrition to include these non-essential elements, we may uncover new pathways to more efficient and sustainable agricultural practices.

Titanium, commonly found in soil and known for its strong structural properties in industrial applications, has been observed to play a beneficial role in plant physiology. Preliminary research suggests that titanium can enhance photosynthetic efficiency and nutrient uptake, contributing to better overall plant growth and disease resistance (Soliman and El-Sherpiny, 2021).

Zirconium, another element not typically associated with plant nutrition, has shown promise in influencing root development and nutrient absorption. Its stable chemical properties might help in the formation of stronger, more resilient root systems, which are crucial for the uptake of water and nutrients (El-Ghamry *et al.* 2024b).

Chromium, often discussed more for its potential toxicity, presents a unique case. At trace levels, chromium has been found to enhance the uptake of other essential nutrients like iron and phosphorus, suggesting a possible role in improving nutrient efficiency and plant growth when carefully managed to avoid harmful effects (López-Bucio *et al.* 2022).

Iodine, an element more commonly linked to human health, is also gaining attention for its role in plant nutrition. Recent studies indicate that iodine can support various physiological processes in plants and enhance resistance to both biotic and abiotic stresses. Its application in iodine-deficient soils could lead to improved crop productivity and quality (Kiferle *et al.* 2021).

The primary objective of this review is to investigate the roles of these four elements in plant nutrition and to evaluate their potential benefits for modern agriculture. By exploring whether elements like titanium, zirconium, chromium, and iodine can be integrated into nutrient management strategies, we aim to provide insights that could lead to more resilient and sustainable farming practices.

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In the following sections, we will discuss the individual roles of titanium, zirconium, chromium, and iodine in plant growth and development. We will examine the current state of research, potential applications, and the implications of incorporating these elements into agricultural practices. Ultimately, this review seeks to broaden the understanding of plant nutrition beyond the conventional essential nutrients, highlighting the promise of non-essential elements in enhancing crop health and productivity.

1. Exploring Non-Essential Elements (Ti, Zr, Cr, I)

Characteristics and attributes of each element

Titanium (Ti)

Titanium, often considered non-essential, has been shown to enhance plant growth under certain conditions. It is known to stimulate enzymatic activities and improve the efficiency of photosynthesis, possibly due to its role in promoting the uptake of other nutrients. Research indicates that titanium might be involved in enhancing disease resistance and improving the overall vigor of plants (Lyu *et al.* 2017).

Titanium is a versatile element renowned for its strength, light weight, and corrosion resistance, making it highly valuable in various industrial and technological applications. Titanium has an atomic number of 22 and is represented by the symbol Ti. Titanium forms various salts, such as titanium dioxide (TiO_2), titanium tetrachloride ($TiCl_4$), and titanium sulfate (Ti $(SO_4)_2$), among others. These salts have diverse applications ranging from pigments in paints to catalysts in chemical reactions. Titanium exhibits high chemical reactivity, especially at elevated temperatures, forming stable oxides and halides (Alshegaihi *et al.* 2024).

The molecular weight of titanium is approximately 47.87 grams per mole (g/mol). Titanium has a relatively low density of around 4.5 g/cm³, which is about 60% that of steel but comparable to aluminum (Gao *et al.* 2024).

Titanium is not typically known for its solubility in agricultural contexts. In fact, titanium is often considered insoluble in water under normal conditions. Its oxide form, titanium dioxide (TiO_2), which is a common form in agriculture and various industrial applications, is particularly insoluble in water. This characteristic makes it less accessible for direct uptake by plants through root absorption (Gázquez et al. 2021).

However, there are some specialized forms of titanium compounds, such as titanium sulfate (Ti $(SO_4)_2$), which are water-soluble and can be used as sources of titanium for agricultural purposes. Titanium sulfate is sometimes applied to soil to provide titanium as a micronutrient supplement for plants, especially in areas where there might be deficiencies or specific needs for enhanced plant growth (Gázquez et al. 2021).

Titanium dioxide, the most common form of titanium in agriculture, is largely insoluble in water, limiting its direct uptake by plants through irrigation or soil application. Some titanium compounds, such as titanium sulfate (Ti $(SO_4)_2$), are soluble in water and can be used as micronutrient supplements for plants (Kolenčík *et al.* 2020; Gázquez *et al.* 2021).

Zirconium (Zr)

Zirconium's role in plant nutrition is not well-documented, but preliminary studies suggest it could have a beneficial effect on root development and nutrient absorption. Zirconium compounds are noted for their stability, and their interaction with plant biochemistry could influence the uptake of other critical nutrients, potentially improving plant health (Shahid *et al.* 2012).

Its chemical symbol is Zr having an atomic number of 40. It is solid at room temperature and its corole is silvery-white. Its density is approximately 6.52 g/cm³ (Chen *et al.* 2020).

Zirconium (Zr) is a transition metal known for its high corrosion resistance and biocompatibility, making it valuable in various industrial and medical applications. In agriculture, zirconium is not traditionally recognized as an essential nutrient for plant growth. However, recent studies have explored its potential beneficial effects, particularly in enhancing root development and overall plant health (Parveen and Siddiqui, 2022).

Zirconium has been found to promote root growth and enhance root system development in plants. This is particularly advantageous in improving nutrient uptake efficiency and overall plant stability (El-Ghamry *et al.* 2024b).

Studies suggest that zirconium application may enhance plant tolerance to various environmental stresses, such as drought and salinity. This can contribute to better crop resilience and productivity in challenging growing conditions. While the mechanisms are still under investigation, zirconium has shown potential in improving the absorption of essential nutrients, such as phosphorus and potassium, which are critical for plant growth and development (Habib *et al.* 2018).

Research on zirconium's role in agriculture is ongoing, with focus on its impact on plant physiology, soil health, and crop productivity. Zirconium can be applied to soils through fertilizers or amendments to assess its effectiveness in enhancing plant growth and nutrient utilization. As with any agricultural input, careful consideration of dosage, application methods, and environmental impact is essential to optimize its benefits and minimize potential drawbacks (Amirov *et al* .2019).

Zirconium, although not traditionally considered an essential plant nutrient, holds promise in agricultural applications due to its potential to improve root development, stress tolerance, and nutrient uptake in plants. Further research and field trials are needed to fully understand its mechanisms of action and to develop practical strategies for its use in sustainable agriculture (Parveen and Siddiqui, 2022; El-Ghamry *et al.* 2024b).

Chromium (Cr)

Chromium's impact on plants is controversial due to its potential toxicity. However, in low concentrations, it may contribute positively by enhancing the uptake of essential nutrients like iron and phosphorus. The challenge lies in balancing the concentrations to avoid detrimental effects while leveraging potential benefits (Nisar, 2020).

Chromium (Cr), a transition metal with the atomic number 24, is primarily recognized for its industrial applications, particularly in stainless steel production and as an alloying agent due to its corrosion resistance and hardness. In agricultural contexts, chromium is not classified as an essential nutrient for plant growth akin to macronutrients like nitrogen or phosphorus. Instead, its role in agriculture centers on its potential influences on plant physiology and metabolism, particularly in specific forms and concentrations.Chromium exists in multiple oxidation states, with chromium (III) and chromium (VI) being the most stable and common forms relevant to environmental and biological systems. Chromium (VI) is notably toxic to plants and can hinder critical processes such as seed germination and root elongation at elevated concentrations, thereby posing environmental risks and necessitating cautious management in agricultural practices to prevent soil and water contamination (Arabi *et al.* 2021).

Despite its potential toxicity, chromium at lower concentrations, particularly as chromium (III), has been studied for its effects on plant metabolism. Research indicates that chromium might impact nitrogen metabolism and enzyme activities within plants, though the precise physiological roles and benefits in enhancing crop yield or resilience remain less understood and require further investigation.

Moreover, there is evidence suggesting that chromium supplementation at controlled levels could potentially improve the uptake of essential nutrients like iron and phosphorus by plants. This suggests a possible role for chromium in enhancing nutrient availability and utilization, which could have implications for optimizing agricultural productivity under specific conditions (Yang *et al.* 2023).

Given its environmental implications and regulatory considerations, the use of chromium-containing substances in agriculture demands careful scrutiny and adherence to sustainable practices. Ongoing research seeks to elucidate chromium's nuanced interactions within agricultural systems, aiming to balance its potential benefits with environmental stewardship and safety (Yang *et al.* 2023).

Generally, while chromium is not essential for plant growth and is associated with toxicity concerns, its potential roles in influencing plant metabolism and nutrient uptake warrant continued investigation. The agricultural community must navigate these complexities to harness any potential benefits of chromium while mitigating environmental risks, ensuring sustainable practices and safeguarding ecosystem health (El-Ghamry *et al.* 2024b).

Iodine (I)

Iodine, although not essential, has been observed to promote plant growth and development. It is believed to play a role in metabolic processes and stress resistance. Recent studies have highlighted iodine's potential to enhance crop yield and quality, especially in iodine-deficient soils (Kiferle *et al.* 2021).

Iodine (I), an essential non-metal halogen element with atomic number 53, is primarily known for its critical role in human health, particularly in thyroid function and overall metabolic regulation. Beyond its significance in human nutrition, iodine has garnered attention in agricultural contexts for its potential benefits in enhancing plant growth and development under specific conditions (Duborská *et al.* 2022).

Iodine exists as a dark violet solid at room temperature, transitioning into a purple vapor when heated. Its chemical properties include a density of approximately 4.93 grams per cubic centimeter (g/cm³), a melting point of about 113.7 degrees Celsius, and a boiling point around 184.3 degrees Celsius. These properties influence its behavior in agricultural applications, affecting its solubility and availability to plants in various soil environments (Maglione *et al.* 2022).

In agriculture, iodine plays a multifaceted role in plant physiology. It participates in essential metabolic processes within plants, including photosynthesis and carbohydrate metabolism. Additionally, iodine is involved in the synthesis of growth regulators, potentially influencing plant growth and development stages crucial for crop yield and quality improvement. Research indicates that iodine supplementation can enhance the uptake of essential nutrients such as nitrogen and phosphorus by plants. By improving nutrient availability in soils, iodine contributes to enhanced plant growth and potentially higher yields. Moreover, iodine has shown promising results in enhancing plant tolerance to environmental stresses, such as salinity and heavy metal toxicity. Its ability to mitigate oxidative stress and enhance plant resilience underscores its potential utility in sustainable agriculture practices (Andrade-Sifuentes *et al.* 2024).

However, the bioavailability of iodine in soils varies significantly based on factors such as soil pH, organic matter content, and microbial activity. Effective application methods, including iodine-enriched fertilizers or foliar sprays, are crucial for maximizing its benefits while minimizing environmental impact. Careful management practices are essential to prevent excessive accumulation of iodine in soil and water systems, which could potentially impact ecosystem health and biodiversity (Zhou *et al.* 2024).

Generally, while iodine is not traditionally classified as an essential nutrient for plants, its emerging roles in enhancing plant physiology, nutrient uptake, and stress tolerance make it a subject of increasing interest in agricultural research. Continued studies are essential to fully understand the mechanisms of iodine's action in plants and to develop practical and sustainable strategies for its application in modern farming practices. By leveraging iodine's potential benefits responsibly, agricultural practitioners can explore new avenues for improving crop productivity and resilience in diverse agricultural settings (Somma *et al.* 2024).

Potential benefits

This section highlights the evolving role of Ti, Zr, Cr and I in agriculture and underscores its potential contribution to enhancing crop resilience and productivity in diverse farming systems. The inclusion of elements like Ti, Zr, Cr, and I in plant nutrition strategies could offer several advantages. By improving nutrient uptake and utilization, these elements might boost plant growth and crop productivity. Elements like iodine can increase plant resilience to environmental stressors (El-Ghamry *et al.* 2024 a, b, c). Leveraging a broader spectrum of elements could lead to more efficient and sustainable agricultural practices. However, it is crucial to consider the risks. Some elements, if not carefully managed, can become toxic to plants. The introduction of new elements into the agricultural ecosystem must be assessed for long-term environmental consequences.

El-Ghamry *et al.* (2018) examined the impact of various titanium soil application rates on lettuce plants grown in sandy soil and irrigated with H. Cooper's nutrient solution. The titanium was applied in the form of titanium dioxide (TiO_2) at rates of 0.0, 25, 50 and 75 ppm. The study found that increasing the titanium application from 0.0 to 25 ppm led to significant improvements in all measured growth parameters of the lettuce plants. However, further increases in titanium dioxide beyond 25 ppm resulted in a notable decline in these parameters. This pattern was also observed for nutrient levels such as N, P, K, Fe, as well as for carotene, vitamin C, chlorophyll a & b and total chlorophyll.

Islam and Ho-Min, (2018) investigated the impact of iodine supplementation on the quality, shelf life, and microbial activity of cherry tomatoes. They supplied iodine at a concentration of 1 mg/L through the nutrient solution for five weeks before harvest. Overall, the study concluded that iodine-treated cherry tomatoes demonstrated significant potential to enhance and preserve quality and shelf life.

Dobosy *et al.* (2020) investigated the uptake and movement of iodine in cabbage and tomato plants grown on various soil types by irrigating with water containing iodine at concentrations of 0.1 and 0.5 mg/L. The study found that these iodine treatments did not significantly affect the photosynthetic efficiency or chlorophyll levels in the leaves of cabbage and tomato. Cabbage grown on sandy and sandy silt soils showed a slight growth stimulation with iodine treatment, while growth remained unchanged on silt soil.

Ghazi *et al.* (2021) investigated the potential of using titanium dioxide (TiO_2) as a replacement for mineral nitrogen fertilizers in sugar beet cultivation. The study involved treatments with and without nitrogen fertilization and examined the effects of titanium dioxide at concentrations of 5.0, 10.0 and 15.0 mg/L. Among the titanium treatments, the combined application method, which included both foliar and soil application, proved to be the most effective. This was followed by foliar application alone, and then soil application alone. The best performance across all application methods was observed at the titanium concentration of 5 mg/L, after which performance declined with increasing titanium concentrations. Specifically, applying titanium at 5.0 mg/L using the combined foliar and soil method yielded the most favorable results.

Soliman and El-Sherpiny, (2021) explored the feasibility of replacing mineral nitrogen fertilizers with titanium (Ti) and vanadium (V) for faba bean cultivation. The treatments involved varying levels of Ti and V at 5.0 and 10.0 mg/L, as well as a control group without these elements. The results indicated that both Ti and V, at the given concentrations, significantly increased the nitrogen content in the leaves. Overall, the study concluded that Ti and V play a crucial role in the non-biological nitrogen fixation process, suggesting their potential as alternatives to traditional nitrogen fertilizers.

Kozlova *et al.* (2021) discussed the potential role of titanium dioxide (TiO_2) in the non-biological fixation of atmospheric nitrogen into nitrate on TiO_2 surfaces. In this context, TiO_2 functions as a catalyst, enabling the conversion of atmospheric nitrogen into nitrate through a series of reactions involving intermediate nitrogen oxide species. When exposed to ultraviolet (UV) light, TiO_2 undergoes a photochemical reaction due to its relatively wide bandgap energy, allowing it to absorb UV light while reflecting or transmitting most visible light. The incident UV light, possessing energy greater than the bandgap energy of TiO_2, generates electron-hole pairs by exciting electrons from the valence band to the conduction band, thus creating positively charged holes in the valence band. These electron-hole pairs can engage in various photochemical reactions. Specifically, they can interact with nitrogen molecules adsorbed on the TiO_2 surface, aiding the conversion of nitrogen gas (N_2) into nitrogen oxides, which subsequently transform into nitrate ions (NO_3^-) in the presence of water and oxygen. This process, known as photocatalysis, describes the nitrogen fixation on TiO_2 surfaces under UV light exposure (Wu *et al.* 2022).

El-Ghamry *et al.* (2022) explored the impact of titanium (Ti) at various concentrations (0.0, 5.0, 10.0, and 15.0 mg/L) on non-biological atmospheric nitrogen fixation and on enhancing sugar beet tolerance to salinity. They found that the combined application of titanium (both foliar and soil) was the most effective approach, followed by foliar application alone, and then soil injection. The optimal titanium concentration was 5.0 mg/L across all application methods, as higher rates resulted in decreased plant yield parameters. Notably, plant performance under control conditions was superior to those treated with 15.0 mg/L of titanium, regardless of the application method. This study highlights the importance of understanding titanium toxicity in plant tissues to ensure its safe and effective use.

Parveen and Siddiqui, (2022) investigated the impact of zirconium dioxide nanoparticles (ZrO_2 NPs) at concentrations of 0.10 and 0.20 g/L on tomato plants, applying them both as a foliar spray and through seed priming. The study found that foliar spray was more effective than seed priming in enhancing plant growth, chlorophyll, carotenoids, proline, and defense enzyme activities, both in the presence and absence of pathogens. The foliar application of 0.20 g/L ZrO_2 NPs resulted in the greatest improvements in these growth parameters and significantly reduced disease indices in the tomato plants.

El-Sherpiny and Faiyad, (2023) evaluated the effects of titanium dioxide (TiO_2) on faba bean plants through various treatments. The primary treatments included: T_1, a control group without titanium or rhizobium inoculant; T_2, soaking seeds in a solution with 6 mg/L titanium before sowing; T_3, using rhizobium inoculant as another control; and T_4, injecting titanium into the soil at a rate of 6 mg/L. Additionally, the sub-main factor was the foliar application of titanium at different rates: F_1, a control without titanium; F_2, 3 mg/L titanium; F_3, 6 mg/L titanium; and F_4, 9 mg/L titanium. The results indicated that the T2 treatment, where seeds were soaked in a titanium solution of 6 mg/L before sowing, yielded the highest nitrogen content in leaves and the best growth performance and productivity, followed by T_3 (rhizobium inoculant), T_4 (soil injection of titanium) and T_1 (control). Regarding foliar applications, there was a notable and progressive impact of titanium on leaf nitrogen content and overall plant growth and productivity. Increasing the titanium concentration from 0.0 mg/L to 3 and 6 mg/L resulted in a gradual enhancement of these traits. However, a significant decline was observed when the titanium concentration was further increased to 9 mg/L.

Elawady *et al.* (2024) evaluated the effects of spraying titanium at varying rates (0.0, 3.0, and 6.0 mg L^{-1}) on the growth performance of crisphead lettuce. The findings indicated that all growth parameters and quality traits progressively improved as the titanium application rate increased from 0.0 to 3.0 to 6.0 mg L^{-1}.

El-Ghamry *et al.* (2024b) investigated the effects of foliar applications of titanium (Ti), zirconium (Zr), chromium (Cr) and iodine (I) on the growth and productivity of crisphead lettuce and red cabbage. These elements were applied at two concentrations, 5.0 and 10 mg/L, with a control group receiving no elemental foliar treatment. The study assessed various growth, physiological and biochemical parameters. All tested elements significantly improved the growth traits and productivity of both crisphead lettuce and red cabbage, with titanium showing the most substantial effects, followed by iodine, chromium, and zirconium, and the control group demonstrating the least improvement. Furthermore, the positive impact on plant performance and productivity increased as the concentration of the elements rose from 5.0 to 10 mg/L.

Based on previous studies, a comparison among titanium (Ti), zirconium (Zr), chromium (Cr), and iodine (I) can be made as shown in Table 1 below:

Table 1. Comparison of Titanium (Ti), Zirconium (Zr), Chromium (Cr), and Iodine (I) for Agricultural Use

Element	Atomic Number	Category	Primary Use in Agriculture	Agricultural Benefits	Toxicity
Titanium (Ti)	22	Transition Metal	Potential use in enhancing nitrogen use efficiency and stress tolerance in plants	Improves plant growth, enhances resistance to abiotic stresses, and potentially increases nitrogen fixation	Low toxicity to plants and humans in its common forms
Zirconium (Zr)	40	Transition Metal	Limited direct agricultural application; potential use in soil conditioners due to chemical stability	Enhances soil structure and stability, though not directly used in agriculture	Low toxicity; inert under most conditions
Chromium (Cr)	24	Transition Metal	Trace element, used in some micronutrient fertilizers; essential in small amounts but toxic in excess	Necessary for some enzymatic functions in plants; involved in metabolic processes but toxic at high levels	Moderate to high toxicity depending on oxidation state; Cr(VI) is highly toxic
Iodine (I)	53	Halogen	Essential micronutrient for animal health; used in disinfectants and plant growth stimulants	Supports thyroid function in animals; used in agriculture to improve plant growth and disease resistance	Low to moderate toxicity; essential in trace amounts, but excessive exposure can lead to toxicity

CONCLUSION

Exploring the nutritional benefits of elements like titanium, zirconium, chromium, and iodine presents a promising frontier in plant science. As we continue to uncover the potential of these elements, there is a significant opportunity to revolutionize agricultural practices and contribute to more sustainable food production systems. Future research should focus on elucidating the precise roles of these elements and their safe application in agriculture.

Conflicts of interest

The authors have declared that no competing interests exist.

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الأسرار الكامنة وراء الأساسيات في تغذية النبات: الإمكانيات الواعدة للتيتانيوم والزركونيوم والكروم واليود: مراجعة مختصرة

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الملخص

في إطار السعي لتحسين تغذية النبات، تستعرض هذه المراجعة الأدوار المحتملة لعناصر التيتانيوم (Ti) والزركونيوم (Zr) والكروم (Cr) واليود (I) في نمو وتطور النباتات. في حين أن تغذية النبات التقليدية تركز على العناصر الكبرى والصغرى الأساسية مثل النيتروجين والفوسفور والبوتاسيوم، تشير الأبحاث الناشئة إلى أن العناصر غير الأساسية قد تقدم فوائد هامة. يُظهر التيتانيوم، على الرغم من عدم كونه ضروريًا، وعدًا بتحسين نمو النبات وكفاءة التمثيل الضوئي من خلال تحفيز الأنشطة الإنزيمية وتعزيز امتصاص العناصر الغذائية. الزركونيوم، الذي غالبًا ما يتم تجاهله، يُقترح أن يكون له تأثير إيجابي على تطوير الجذور والصحة العامة للنبات، على الرغم من أن الأبحاث حوله ما زالت في مراحلها الأولى. الكروم، المعروف بسمّيته عند مستويات عالية، قد يُعزز امتصاص العناصر الغذائية الأساسية عند مستويات ضئيلة، خاصة الحديد والفوسفور، مما يُساهم في تحمل الإجهاد. أما اليود، الذي لا يُعتبر تقليديًا ضروريًا للنباتات، فقد لوحظ أنه يدعم العمليات الفسيولوجية ويزيد من مقاومة النباتات للإجهادات الحيوية وغير الحيوية، خاصة في التربة التي تعاني من نقص اليود. قد يؤدي إدراج هذه العناصر في برامج تغذية النبات إلى إحداث ثورة في الممارسات الزراعية، حيث يوفر أدوات جديدة لتحقيق إنتاج غذائي مستدام وفعال. ومع ذلك، فإن الإدارة الحذرة لهذه العناصر ضرورية لتجنب السمية والتأثيرات البيئية السلبية. هناك حاجة إلى المزيد من الأبحاث لفهم الآليات الخاصة بهذه العناصر ووضع إرشادات آمنة وفعالة لاستخدامها. بصفة عامة، يمثل استكشاف الفوائد الغذائية للعناصر غير الأساسية مثل التيتانيوم والزركونيوم والكروم واليود جبهة واعدة في علم الزراعة، مما قد يعزز من مرونة وإنتاجية المحاصيل في مواجهة التحديات العالمية.