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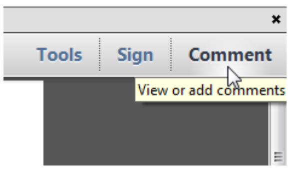

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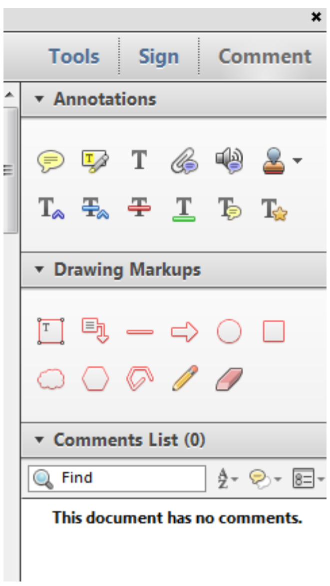

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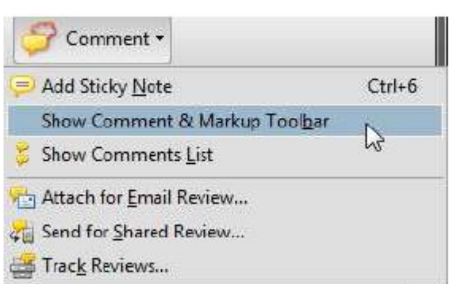

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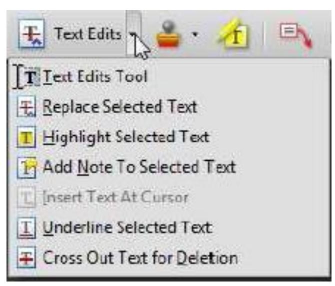

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AQ1-AQ4 EDITORIAL

Essential trace metals: micronutrients with large impact

Among the metals found in the environment, plants utilize copper, iron, manganese, molybdenum, nickel, and zinc as micronutrients. Understanding of their uptake, behaviour in plant cells, and interactions at the molecular level is essential not only to improve plant nutrition and crop yield but also to improve human diet. The translation of experimental results obtained in model species to crops is an important goal that will eventually help improve micronutrient levels in food. This review collection discusses current state of the art and possible future directions related to the plant–essential metal relationship, including both basic molecular research and applied aspects related to agriculture and human nutrition.

One of the earliest research fields in experimental plant sciences deals with the plant–metal relationship. From the 18th century, this field has examined in detail the uptake, accumulation, translocation, speciation, and physiological role of trace metals, as well as the diverse effects of their deficiency and excess on plant physiology and molecular processes. Owing to the active research in the past decades, specific primary and secondary active transport systems have been revealed through which land plants are able to absorb, distribute, and sequester essential metal ions. Essential trace metals have diverse biological roles in plants, but in general they are enzyme cofactors and participate in vital processes such as the mitochondrial and photosynthetic electron transport chains, CO_2 fixation, the antioxidant defence system, nitrogen and sulfur metabolism, and phytohormone synthesis. The limited amount or bioavailability of essential metals causes various deficiency symptoms in plants, such as growth retardation, yellowing, susceptibility to abiotic and biotic stresses, and yield reduction. Furthermore, plant nutrient deficiencies are closely related to human malnutrition, which is partly due to the importance of plant-based diets in human nutrition. Beyond enrichment through agricultural biofortification practices (e.g. fertilization), crop breeding for higher mineral micronutrient content is an available strategy to alleviate trace metal deficiencies in humans.

Some of the articles in this special issue summarize the latest molecular-level knowledge and emphasize future directions, while others focus on applied aspects in plant essential metal homeostasis research. All the authors draw attention to the need for a better knowledge of trace metal homeostasis.

Zinc and iron homeostasis in plants: understanding of molecular mechanisms

It has long been known that zinc (Zn) has diverse regulatory functions in a wide range of plant proteins, including enzymes and transcription factors (Broadley *et al.*, 2007). However, the question of which processes regulate the availability of Zn in the cell for proteins, transporters, and sensor partners remains unanswered. The review by Clemens (2022) details the intracellular forms and distribution of Zn, which determine 'free Zn' and 'Zn buffers', that is, Zn bound by metabolites or peptides. The main Zn storage organelles are the vacuole and the endoplasmic reticulum, and the influx and efflux transporters localized in their membranes serve as a dynamic control of local Zn concentrations in space and time. Based on results obtained in animal systems, the author rightly assumes that spatially controlled cytosolic Zn may also modulate phosphorylation cascades and influence protein–protein interactions in plant cells.

Owing to the diverse biological role of Zn and its frequently limited availability in soils, Zn deficiency in plants has received special attention in basic molecular biology research (Assunção *et al.*, 2010; Campos *et al.*, 2017; Lilay *et al.*, 2021). Thiébaut and Hanikenne (2022) provide a valuable summary of the knowledge gained so far in Arabidopsis, which emphasizes the urgent need for this knowledge to be translated to dicotyledonous crop species. They consider Zn requirements, the impact of Zn deficiency, the function and regulation of Zn transporters, Zn sensing, and the role of phytohormones in the Zn deficiency response in economically important dicot crops, providing a gap-filling review of the field.

Iron (Fe) deficiency is one of the most common nutrient deficiencies in the world, and multiple studies have therefore focused on Fe uptake, transport, and homeostasis in plants (e.g. Hell and Stephan, 2003). Although a lot of attention has been given to Fe uptake by roots in order to biofortify crops and limit dietary Fe deficiency in humans, less information is available on Fe metabolism in leaves. In their review, Sági-Kazár *et al.* (2022) focus on the Fe–ligand interactions in leaves and their role in cellular Fe distribution. Owing to the redox-active properties of this element, Fe homeostasis needs to be controlled to avoid Fe deficiency as well as toxicity. Hence, the authors further discuss how Fe is incorporated into Fe-containing cofactors and enzymes and stored under supraoptimal conditions, and address the role of subcellular organelles such as chloroplasts and mitochondria. It is clear that intracellular monitoring of the Fe status is key to activating proper cellular responses in developing leaves and, although some data are available, this timely review highlights new research avenues.

Under conditions of metal deficiency, the regulation of metal distribution needs to be modified to prioritize essential metalloproteins. In the review of Perea-García *et al.* (2022), post-transcriptional modulators of metalloprotein messenger RNA (ModMeR) are proposed as internal metal distribution 'valves' to finely adjust metalation ranking. They illustrate this concept with copper-microRNAs from *Arabidopsis thaliana* and iron ModMeR in yeast, mammals, and bacteria.

Interaction between trace metal homeostasis and abiotic stress

Plants are in continuous interactions with their immediate environment, and in addition, trace elements that make up the plant metallome interact in a complex way (Andresen *et al.*, 2018). This holistic aspect is discussed by Lešková *et al.* (2022), who summarize the essential trace metal-induced changes in nutrient availability through the excretion of protons and metabolites and through the influence of the rhizosphere microbiota. Metal nutrient interactions at the level of transporters and signalling are also discussed. The root structure, which influences nutrient uptake, is modified by the absence or excess of essential metals and elemental interactions. The authors highlight the importance of extending the trace metal-associated research to other plants beyond model species to improve breeding practices.

Abiotic stresses other than metal deficiencies are also addressed in this special issue. Recent evidence suggests that molybdenum (Mo), which is another micronutrient required by almost all living organisms, is more than an essential element for plant growth and development. X-Y. Huang *et al.* (2022) review recent research progress on molybdate uptake and transport and the Mo homeostasis network in plants, and discuss the potential roles of molybdate transporters in plant adaptation to a coastal environment characterized by salinity.

Both elevated temperatures due to climate change and frequent suboptimal nutrient availability in agricultural soils justify the extensive research on the bidirectional relationship of heat stress and plant metal homeostasis, which is the topic of the timely review of Hendrix *et al.* (2022). The authors examine the effects of elevated temperatures on plant trace metal homeostasis, which mainly result from changes in the soil availability of metals, changes in root structure, or heat-induced changes in the function of transporter proteins. Examples of the involvement of trace metals in thermotolerance, including heat-induced ferroptosis, the role of Fe-related glutaredoxins, and copper-related microRNA398, are highlighted.

Trace metal homeostasis of plants: importance in agriculture and human nutrition

As mentioned in the review by Assunção et al. (2022), micronutrient deficiencies in cultivated soils and plants impact crop production (in terms of growth as well as tolerance of abiotic and biotic stresses) and human health. The authors describe strategies to identify new crop varieties with higher micronutrient content, and challenges in research on plant micronutrient homeostasis.

Zn deficiency is the most common micronutrient deficiency, affecting more than 50% of the world's agricultural soils. While Thiébaut and Hanikenne (2022) focus on Zn homeostasis in Arabidopsis and related dicot crops, S. Huang *et al.* (2022) review Zn transporters in rice. They give examples of improving the content and bioavailability of Zn in rice grains by manipulating genes highly expressed in the nodes, where Zn is highly deposited. As well as Zn biofortification, tolerance to Zn deficiency is also an important trait for rice breeding. In relation to these goals, S. Huang *et al.* highlight the importance of wild rice as a helpful resource to breed new crops.

Fe nutrition in crops is an important challenge for agriculture and human nutrition. Murgia *et al.* (2022) discuss several aspects of Fe homeostasis that may be useful to improve Fe content in plants. In particular, they present a model of possible interactions between the microbiota present in the rhizosphere, plant immunity, and Fe homeostasis. Beneficial rhizobacteria are a useful tool to induce systemic resistance (a type of plant immune response) and increase Fe uptake from soil, serving as both biopesticides and fertilizers. Murgia *et al.* also outline the process of seed loading with Fe and underline the importance for crop breeding of wild relatives that have higher Fe content in the seeds than modern cultivars.

As fertilization is crucial in the biofortification of crops, the quest for environmentally friendly and sustainable agricultural technologies remains a challenge. Kolbert *et al.* (2022) highlight the potential of using nanometals in crop production, which opens a new field of applied research in sustainable agriculture. As size and shape define the characteristics of nanometals, there exists the potential to produce well-defined nanoforms of essential metals with optimal features. For this, in an initial phase, detailed knowledge on the root and foliar uptake of these nanometals, as well as their biotransformation within cells, is needed. In a second step, the potential beneficial effect of nanometals on crop yield needs to be investigated using a holistic approach at different levels of biological organization. Finally, the authors address the translation from the observed hormetic effects of nanometals on plant performance, that is, growth and development, production of phytochemicals, and improved stress tolerance, to their potential application in agricultural practices.

Conclusion and future perspectives

The healthy balance of trace metal homeostasis in plants is closely related to human health, the latter receiving more attention during the Covid-19 pandemic than before. Thus, plant biologists and agricultural specialists have a great responsibility to develop plant-based solutions for alleviating human malnutrition. It is easy to acknowledge that comprehensive preliminary research is needed to understand the complex transport and translocation processes for trace metals and to identify responsible genes and gene products as future targets of modification. Accordingly, current research on plant trace metal homeostasis points towards two main directions. First, basic molecular processes related to trace metal assimilation, deficiency, and excess continue to be explored, primarily in monocot and dicot model plants such as rice and *Arabidopsis thaliana*. Significantly less information is available about trace metal homeostasis in crops beyond model species (e.g. rapeseed, wheat, tomato), and extending research beyond model species may provide important, gap-filling results in the future. Secondly, other studies on plant trace metal homeostasis direct attention to aspects associated with crop cultivation and human nutrition. It is crucial to better understand the molecular processes of accumulation of essential metals in edible plant parts (e.g. leaves, seeds) to implement effective enrichment practices providing metals utilized for human nutrition without negatively affecting plants' life processes, that is, growth and development. It is also important to introduce new sustainable crop production strategies and accurately assess the effects at the physiological and molecular levels, as well as their safe application in the environment.

In conclusion, in this old field of plant biology research directly related to human health, a huge amount of knowledge has been gained, which must be extended in future research to face challenges related to crop production in a context of global change and increased demands for plant-derived products, such as food, feed, and biomaterials. This predicts exciting decades ahead of us in plant trace metal research.

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