INFLUENCE OF MINERAL FERTILIZERS ON NUTRITIONAL QUALITY OF STAPLE FOOD CROPS

Wiesler, **F.**
Institute of Plant Nutrition, University of Hannover, Germany

Gerendás, **J.,** and **Sattelmacher**, **B.**
Institute of Plant Nutrition and Soil Science, University of Kiel, Germany

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Summary

A major challenge for modern agriculture is to reconcile productivity and sustainability of production systems and nutritional quality of food products. Nutritional quality is a highly complex trait due to both (i) the large number of individual properties which determine crop quality (i.e.,concentration and bioavailability of essential and potentially toxic minerals, organic nutrients and accessory health factors) and (ii) the various factors which control them (i.e.,genetic and exogenous factors, the latter either natural or man-made). In the present article, selected examples are given showing that nutrient supply influences yield and quality of food crops often non-synchronously. Maximum quality can be obtained either before or after the maximum dry or fresh matter yield has been reached. Numerous studies have shown, for example, that high N supply may negatively affect quality characteristics, such as nitrate accumulation in vegetables, starch concentration in potatoes, sucrose concentration in sugar beet, oil concentration in oil crops, ascorbic acid concentration in vegetables and the nutritional value of proteins. On the other hand, high N supply may increase the concentration of proteins

and also the concentrations of some vitamins, e.g., carotene and thiamin. A synchronous pattern of yield and quality curves is the exception rather than the rule. In view of overall quality integrated fertilization strategies should aim rather at an optimization of the various quality properties than at a maximization of single properties. The effects of accessory health factors and antinutrients on human health in general and the influence of mineral fertilization on the concentration of these compounds in particular require further studies. At present, an assessment of many of these compounds regarding their actual impact on human health is often complicated by the fact that the same compound (e.g., phytic acid) may simultaneously show both typical features of an antinutrient (e.g., inhibition of mineral element bioavailability) and typical features of an accessory health factor (e.g., anticarcinogenic activity).

1. Introduction

To meet the food requirements of a growing world population, intensification of crop production was a major challenge for agriculture in the past and will remain essential in the future, particularly in developing countries with high population pressure. Enormous increases of crop yields in the past decades were mainly brought about by the introduction of 'Green Revolution' technologies, i.e., the cultivation of new, high-yielding varieties along with increasing use of mineral fertilizers and crop protection chemicals. However, during the Green Revolutions push toward food security, little attention was given to (i) adverse environmental impacts of modern agricultural practices, and (ii) nutritional quality of food crops. Then, starting in the late 1970s, increasing environmental concern resulted in considerable efforts to improve the sustainability of modern agricultural production systems, for example by more efficient use of mineral fertilizers. Quality of food crops as a practical problem in human nutrition, though recognized since many years, only received growing attention during the 1990s, due to various studies which indicated that there is a lack of adequate, balanced nutrition in many countries, resulting in poor health, low productivity and an increase of chronic diseases, especially in low-income families. In recent publications, it has been emphasized, therefore, that a new paradigm ('food system paradigm') for world agriculture is needed, aiming at productivity, sustainability and nutritional quality of food products. However, when paying more attention to plant quality, we are confronted with the high complexity of this trait, due to both (i) the large number of individual properties which determine crop quality and (ii) the various genetic and exogenous factors which control them. These aspects will be outlined in the following sections, followed by the presentation of selected examples demonstrating the effects of mineral nutrition on nutritional quality of food crops.

1.1. Properties Determining Plant Quality

Overall quality may be defined as the sum (or product) of individual properties that enable a plant or plant product to meet the requirements of a user or consumer. Table 1 shows that overall quality depends on both physical and chemical plant properties. Physical properties determine nearly exclusively the outward appearance and thus the marketable yield of vegetables and fruits for direct consumption. To achieve required quality standards, vegetable growers often apply very high doses of nitrogen, irrespective of adverse environmental impacts and the nutritional quality of the product.

Nutritional and sensory quality are, however, mainly determined by the chemical composition of a plant including both quality-improving and quality-reducing compounds. Quality may be improved by high concentrations of essential minerals, carbohydrates, nitrogenous compounds, such as essential amino acids, lipids, organic acids, flavors, vitamins and bioactive compounds (secondary compounds or accessory health factors). Most of these groups of substances also include, however, quality-reducing compounds, for example heavy metals, nitrate, oxalate and so-called antinutrients. It is worth mentioning that a number of compounds (e.g., phytic acid, dietary fiber) simultaneously show typical features of an antinutrient (e.g., due to adverse effects on mineral element bioavailability), as well as typical features of an accessory health factor (e.g., due to anticarcinogenic activity). In contrast to marketable yield and nutritional quality, processing quality (including cooking quality) depends on both physical and chemical properties of the harvested plant part. In addition to these parameters directly determining crop quality, one may also include production quality, i.e., environmental impacts of crop production, into an overall quality concept.

Physical characteristics	Chemical composition
• Shape • Size • Weight • Color • Freshness • Ripeness • Texture • Absence of defects, diseases and pests	• Minerals • Carbohydrates • Nitrogenous compounds • Lipids • Organic acids • Vitamins • Flavors • Bioactive compounds • Antinutrients • Pesticide residues

Table 1. Properties determining plant quality

1.2. Factors Controlling Plant Quality

Plant quality is predominantly controlled by genetic and physiological factors. This becomes obvious in a comparison of species (e.g., low protein concentration in cassava roots compared with cereal grains and legume seeds, relatively low protein concentration in rice grains compared with other cereal grains), cultivars (e.g., protein nutritional quality of conventional and quality protein maize (QPM) or conventional and high-lysine barley), plant organs (e.g., mineral element or nitrate concentration in vegetative and reproductive plant organs) and tissues (e.g., minerals and essential amino acids in the bran and endosperm of cereal grains). These examples demonstrate the outstanding importance of dietary diversity for a balanced and healthy nutrition in humans. Furthermore, the existence of sufficient genetic variation clearly indicates that nutritional quality of crops may be improved by both conventional breeding and molecular genetic approaches (*see other articles in this book dealing with this aspect*). However, within existing genetic boundaries, exogenous factors, either natural (e.g., climate and soil fertility, pest pressure) or anthropogenic (e.g., soil cultivation, fertilization, irrigation, air and soil pollution, plant protection, harvest time and harvest method, postharvest treatments, transport, storage and processing) may considerably modify the quality of plant products. These factors may have a special relevance in those situations where food diversity is low, due either to traditional eating habits, or limited access to diverse foods in low-income families.

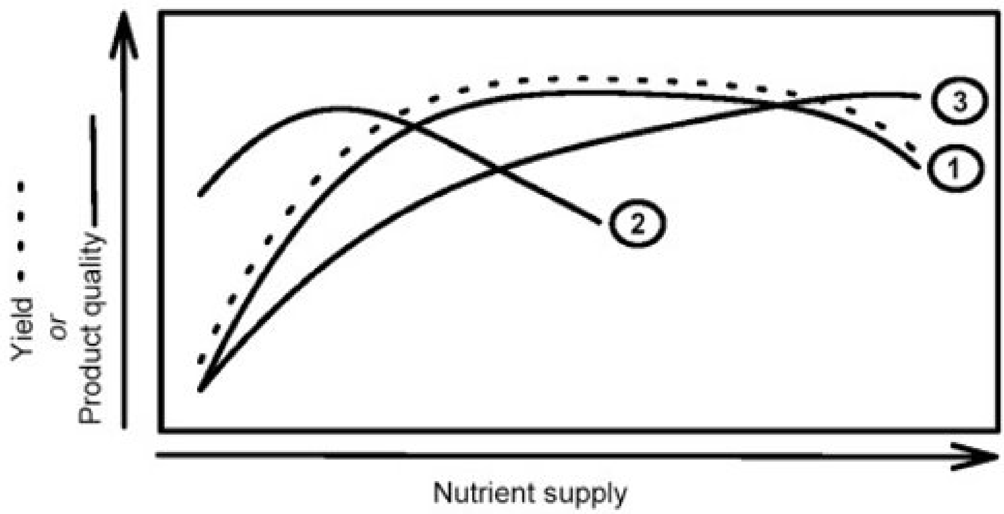

Figure 1. Yield (dotted curve) and product quality (curves 1, 2 and 3) as influenced by nutrient supply. For examples see text. Based on Marschner H. (1995). *Mineral Nutrition of Higher Plants*. London: Academic Press.

Mineral nutrient supply may influence all quality traits listed in Table 1. As already mentioned above, the need for adequate food supply will require raising crop yields and thus an increased use of fertilizers in the future. However, in assessing the prospects for a maximization of both yield and quality, we have to consider that these traits are often not increased synchronously by the amount of nutrient supply. As shown schematically in Figure 1, maximum quality can be obtained either before (curve 2) or after (curve 3) the maximum dry or fresh matter yield has been reached. A synchronous pattern of yield and quality curves (curve 1) is the exception rather than the rule. Examples for curve 2 are nitrogen supply and quality characteristics, such as low nitrate concentrations in vegetables, starch concentration in potatoes and cereal grains, sucrose concentration in sugar beet, oil concentration in oil crops, nutritional value of proteins and ascorbic acid concentration in vegetables. On the other hand, maximum quality may require a higher nutrient supply than necessary for maximum yield, for example to achieve high gluten concentrations in baking wheat or high mineral element concentration in cereal grains. Figure 1 clearly indicates that reverse relationships may exist between mineral element supply and different quality properties, for example between outward and internal quality of a crop (e.g., green color and nitrate concentration in vegetables) and also between various internal quality parameters (e.g., protein concentration and nutritional value of proteins). The situation becomes even more complicated if we include production quality into an overall quality concept. For example, if large amounts of fertilizers are applied to improve the outward quality of vegetables or gluten concentration in cereal grains, the environment may be adversely affected by low fertilizer N recovery.

Plant nutrition affects plant quality not only through the amount of nutrient supply, but also through a number of other factors listed in Table 2. All these factors should be considered when integrated fertilization strategies considering yield, product quality and production quality are developed. In the following sections, selected examples demonstrating the influence of mineral fertilization on the chemical composition of plants and thus its nutritional quality will be presented.

Measure	Example
• Amount of nutrient supply by soil and fertilizers	N, K, Ca, Mg, P, S, Cl, B, Fe, Mn, Zn, Cu, Mo, Ni, (Na, Se, Cr, I, F)
• Nutrient ratios	K/Ca ratio
• Nutrient form	NH_4^+ *vs.* NO_3^- Cl^-- *vs.* SO_4^{2-} salts Salts *vs.* chelates Mineral *vs.* organic fertilizers
• Technique of application	Broadcast *vs.* banded Soil *vs.* foliar
• Timing of application	Late N application with baking wheat
• Post-harvest treatments	Ca infiltration of apple fruits
• Minor components of fertilizers	Cd in P fertilizers
• Side effects of fertilizers	Nutrient effects on plant diseases and pests

Table 2. Measures of plant nutrition influencing the quality of plant products

2. Selected Examples Demonstrating the Influence of Mineral Fertilizers on Nutritional Quality of Crops

2.1. Minerals

All minerals essential for plant growth (i.e., calcium, Ca; potassium, K; magnesium, Mg; phosphorus, P; chlorine, Cl; iron, Fe; zinc, Zn; copper, Cu; manganese, Mn; molybdenum, Mo; boron, B and - in form of amino acids - nitrogen, N; and sulfur, S) and, additionally, several other elements (sodium, Na; iodine, I; fluorine, F; selenium, Se; chromium, Cr) are considered essential for humans. Some evidence suggests that several ultra-trace elements (e.g., arsenic, As; nickel, Ni; silicon, Si) are also essential nutrients for animals, although deficiencies in humans have not been described. In addition to being essential for growth and metabolism, and their effects in preventing the classical mineral deficiency diseases (e.g., anemia caused by Fe deficiency, goiter and cretinism caused by iodine deficiency, myocardiopathy caused by Se deficiency ('Keshan disease')), some minerals are known to be significant contributors to the reduction in the risk of contracting chronic diseases, such as cancer, cardiovascular diseases and degenerative diseases associated with aging. All essential elements may cause nutrient imbalances and toxicity in humans (namely Cu, Cr, F, Mo, Ni, Se or Zn) when intake persistently exceeds requirement. Health risks may also be caused by excess intake of other trace elements, such as arsenic (As), cadmium (Cd), mercury (Hg) or lead (Pb).

Mineral malnutrition is widespread, but there are large variations in prevalence of specific deficiencies across geographical and socioeconomic divisions (see *Global Prevalence of Micronutrient Malnutrition and its Impacts on the Health of Children*). Minerals of particular concern are Ca, Mg, Fe, Zn, I, and Se. Although developing countries often have a higher incidence of mineral deficiency, intakes of minerals below the Recommended Dietary Intakes (RDAs) are not confined to those countries. For example, total diet studies in the USA indicated that average intakes of Ca, Mg, Fe, Zn and Cu were below recommended amounts for some age-sex groups. Before discussing the effect of mineral fertilization on the mineral element concentration in plant foods, it should be emphasized that no single plant species, regardless of growing conditions and agricultural practices, can supply all of the mineral requirements of humans, again highlighting the importance of dietary diversity for healthy nutrition. For the minerals of particular concern, the richest sources in human diets are dairy products (Ca), meat (Fe, Zn, Se in liver and kidney), fish (Se, I), certain vegetables (Mg, Ca, Fe, Zn), whole grain products (Zn, Se), wheat bran (Mg), legume seeds (Mg, Fe, Zn) and nuts (Mg, Se in Brazil nuts). Cereal grains are nearly always very low in Ca, rice grains are especially low in Fe and Zn, and milk and many vegetables and fruits contain little Se.

2.1.1. Concentration of Essential Minerals of Particular Concern

2.1.1.1. Calcium and Magnesium

The range of calcium concentrations in plants is predominantly a characteristic of the plant species or plant organ, and is less dependent on the level of available Ca in the soil. An increase in the concentration of Ca in the external solution may lead to an increase in the Ca concentration in leafy vegetables, but not necessarily in low-transpiring organs such as fleshy fruits, tubers and grains supplied predominately via the phloem. However, on soils with appreciable cation-exchange capacity (CEC) and for non-legume crops, calcium concentration in soil solution is rarely a limiting factor for Ca uptake. Since Ca transport to the roots via mass flow often exceeds Ca absorption by the roots, Ca concentration in the rhizosphere is often higher than in the bulk soil. Only soils that are highly weathered have a low pH, and low CEC may supply calcium inadequately for plant growth. Under these conditions, amelioration of the soil acidity by liming is essential to improve plant growth, and may also increase the Ca concentration in the plant. Most commonly used are limestone or dolomite ($CaCO_3$ with varying amounts of $MgCO_3$), but slag and other materials are also appropriate. For example, rock phosphates have a liming effect and, additionally, they provide Ca. It should be considered that liming is not always an easy to handle technique because of (i) the risk of over-liming which may induce deficiency of P and micronutrients, and (ii) the slow downward movement and thus low efficacy of Ca from the lime particles. Ca salts, such as $CaSO_4$ or $CaCl_2$ and mineral N-sources containing $Ca(NO_3)_2$ may also be used to increase Ca tissue concentration, whereas acid-forming $(NH_4)_2SO_4$ may reduce tissue Ca. To increase the Ca concentration in leaves or fruits, more effective measures than simply increasing the Ca supply should be considered, namely the avoidance of high concentrations of competing ions in the soil solution (K^+, NH_4^+, Mg^{2+}) and increasing the xylem flow into low-transpiring organs (increasing the root pressure, avoidance of high salt concentrations in the substrate, raising the relative humidity during the night, leaf pruning). Although Ca concentration varies considerably between plant species, and may be moderately increased by agricultural practices, it should be emphasized that recommended intakes are barely achieved without the consumption of milk, dairy products or Ca-fortified products.

Deficiency of available magnesium in the soil and suboptimum Mg levels in plants may be caused by low-Mg parent rock materials, Mg leaching and unbalanced NPK fertilization. Deficiency is accentuated by low soil pH and high concentrations of competing ions in the soil solution. In clear contrast to Ca, correction of soil Mg deficiency may not only increase the Mg concentration in leaves but, due to its higher mobility in plants, also in seeds and grains. Various Mg salts, such as $MgSO_4$ H_2O, $MgSO_4$ 7 H_2O and $MgCl_2$ or dolomite ($CaCO_3$ + $MgCO_3$), may be used to avoid Mg deficiency. Similar to Ca, care should be taken to avoid induced Mg deficiency through competing ions,such as H^+, K^+, NH_4^+, Ca^{2+} and Mn^{2+}.

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Biographical Sketches

Franz Wiesler is assistant professor at the University of Hannover, Faculty of Horticulture. He obtained his M.Sc. and Ph.D. degrees from the University of Hohenheim in 1985 and 1991, respectively, and the *venia legendi* (habilitation) from the University of Hannover in 1998. His main teaching and research activities focus on the analysis of factors that contribute to genetic variation in nitrogen efficiency of crop plants and on the optimization of fertilization strategies considering productivity, sustainability and product quality in plant production. Dr. Wiesler was invited to teach his course "Mineral Nutrition and Plant Quality" in several university and governmental institutions in Germany and abroad. He serves as a referee for scientific journals and research funds, and is a member of the consulting editorial board of *Plant and Soil*.

Jóska Gerendás is assistant professor, Faculty of Agriculture, University of Kiel and obtained the M.S. degree (1988) and Ph.D. (1992) from the same university. His Ph.D. thesis entitled 'Influence of form and concentration of nitrogen supply on growth and physiology of young maize (*Zea mays* L.) plants (in German)' focused on physiological aspects of N nutrition, partly using *in vivo* NMR to investigate plant N metabolism and pH regulation, in collaboration with Prof. R. G. Ratcliffe at Oxford University. The characterization of nickel as an essential element for plants was another research interest, and in recent years he has focused on the interaction of mineral nutrition and product quality. He published more than 30 refereed journal articles. Dr. Gerendás' teaching duties focus on mineral fertilization and the influence of plant mineral nutrition on the quality of harvested products.

Burkhard Sattelmacher is professor, Faculty of Agriculture, University of Kiel. He earned the M.S. degrees (1974) and the Ph.D. (1977) from the Free University, Berlin. After a postdoctoral period at the International Potato Center in Peru, he worked as a an assistant professor at the Institute of Plant Nutrition of the University Hohenheim (Prof. Marschner) before he became a full professor at Kiel University (1985). His research program at the University of Kiel focuses on the physiological aspects of plant mineral nutrition. Special attention is paid to the genetic aspects, water relations and the significance of the apoplast. He has served on numerous editorial boards and has published over 100 refereed journal articles.