2 Mineral Deficiencies and Toxicities

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2.1 Nitrogen deficiency

Function and mobility of N

Nitrogen promotes rapid growth and increases leaf size and spikelet number per panicle. N affects all parameters that contribute to yield. Leaf color, an indicator of crop N status, is closely related to the rate of leaf photosynthesis and crop production. When sufficient N is applied to the crop, the demand for other nutrients such as P and K increases.

N-deficiency symptoms and effects on growth

Stunted, yellowish plants. Older leaves or whole plants are yellowish green (Annex A-7, A-10, A-13).

Causes of N deficiency

- Low soil N-supplying power.
- Insufficient application of mineral N fertilizer.
- Low N fertilizer-use efficiency (losses from volatilization, denitrification, incorrect timing and placement, leaching, or runoff).

The soil N supply is commonly not sufficient to support higher yields of modern varieties so that N deficiency is common in all major rice-growing areas. Significant yield responses to fertilizer N are obtained in nearly all lowland rice soils.

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Occurrence of N deficiency

- Soils with very low soil organic matter content (e.g., <0.5% organic C, coarse-textured acid soils).
- Soils with poor indigenous N supply (e.g., acid-sulfate soils, saline soils, P-deficient soils, poorly drained wetland soils).
- Alkaline and calcareous soils poor in soil organic matter.

Effect of submergence on N availability and uptake

If NH_4-N fertilizers (e.g., urea) are incorporated into the reduced soil layer after submergence, NH_4^+ is adsorbed on soil colloids, temporarily immobilized by soil microbes, or bound abiotically to components of soil organic matter such as phenol compounds. Losses from percolation are usually small, except in very coarse-textured soils.

Topdressed urea is rapidly hydrolyzed (within 2–4 days) and is susceptible to loss by NH_3 volatilization. After the midtillering phase, by which time a dense root system with many superficial roots has formed, plant uptake rates of N broadcast into standing water may be large (≤10 kg per ha and day) such that losses from NH_3 volatilization are small.

General N management

Treatment of N deficiency is easy and response to N fertilizer is rapid. The response may already be evident after 2–3 days (greening, improved vegetative growth). Dynamic soil-based and plant-based management are required to optimize N-use efficiency for each season (see Section 1.8).

2.2 Phosphorus deficiency

Function and mobility of P

Phosphorus is essential for energy storage and transfer in plants. P is mobile within the plant and promotes tillering, root development, early flowering, and ripening. It is particularly important in early growth stages.

P-deficiency symptoms and effects on growth

Stunted dark green plants with erect leaves and reduced tillering (Annex A-10, A-15).

Deficiency in soil

For lowland rice soils with little or no free $CaCO_3$, Olsen-P and Bray-1 P test results can be classified as follows:

Response to P	Olsen P	Bray-1 P (mg P per kg)
Highly likely	<5	<7
Probable	5–10	7–20
Only at high yields	>10	>20

Causes of P deficiency

- Low indigenous soil P-supplying power.
- Insufficient application of mineral P fertilizer.
- Low efficiency of applied P fertilizer because of high P-fixation capacity in soil or erosion losses (in upland rice fields only).
- Excessive use of N fertilizer with insufficient P application.
- Cultivar differences in susceptibility to P deficiency and response to P fertilizer.

- Crop establishment method (P deficiency is more likely in direct-seeded rice, where plant density is high and root systems are shallow).

Soils particularly prone to P deficiency

- Coarse-textured soils containing small amounts of organic matter and small P reserves.
- Calcareous, saline, and sodic soils.
- Volcanic (strongly P-fixing), peat, and acid-sulfate soils.

Occurrence of P deficiency

- Excessive use of N or N + K fertilizers with insufficient P application.

Effect of submergence on P availability and uptake

Flooding of dry soil causes an increase in the availability of P in the soil.

General P management

P requires a long-term management strategy. P fertilizer application provides a residual effect that can persist for several years. Management must emphasize the buildup and maintenance of adequate soil-available P levels to ensure that P supply does not limit crop growth, grain yield, and N-use efficiency (see Section 1.8).

2.3 Potassium deficiency

Function and mobility of K

Potassium has essential functions in plant cells and is required for the transport of the products of photosynthesis. K provides strength to plant cell walls and contributes to greater canopy photosynthesis and crop growth. Unlike N and P, K does not have a pronounced effect on tillering. K increases the number of spikelets per panicle, percentage of filled grains, and 1,000-grain weight.

K-deficiency symptoms and effects on growth

Dark green plants with yellowish brown leaf margins or dark brown necrotic spots first appear on the tips of older leaves (Annex A-10, A-17).

Incidence of diseases (brown leaf spot, cercospora leaf spot, bacterial leaf blight, sheath blight, sheath rot, stem rot, and blast) is greater where excessive N fertilizer and insufficient K fertilizer have been used.

Deficiency in soil

For lowland rice soils, exchangeable K soil test results can be classified as follows:

Response to K	Exchangeable K ($cmol_c$/kg)
Highly likely	<0.15
Probable	0.15–0.45
Only at high yields	>0.45

On lowland rice soils with strong K “fixation,” the amount of 1N NH_4OAc-extractable K is often small (<0.2 cmolc /kg) and is not a reliable soil test for assessing K supply.

Causes of K deficiency

- Low soil K-supplying capacity.
- Insufficient application of mineral K fertilizer.
- Complete removal of straw.
- Small inputs of K in irrigation water.
- Low recovery efficiency of applied K fertilizer because of high soil K-fixation capacity or leaching losses.
- Presence of excessive amounts of reduced substances in poorly drained soils (e.g., H_2S, organic acids, Fe^{2+}), resulting in retarded root growth and K uptake.
- Wide Na:K, Mg:K, or Ca:K ratios in soil, and sodic/saline conditions. Excess Mg in soils derived from ultrabasic rocks. Large bicarbonate concentration in irrigation water.

Occurrence of K deficiency

- Excessive use of N or N + P fertilizers with insufficient K application.
- In direct-sown rice during early growth stages, when the plant population is large and root system is shallow.
- In hybrid rice because of greater demand for K.

Soils particularly prone to K deficiency

- Coarse-textured soils with low CEC and small K reserves.
- Highly weathered acid soils with low CEC and low K reserves.
- Lowland clay soils with high K fixation because of the presence of large amounts of 2:1 layer clay minerals.
- Soils with a large K content but very wide (Ca + Mg):K ratio.
- Leached, “old” acid-sulfate soils.
- Poorly drained and strongly reducing soils.
- Organic soils.

Effect of submergence on K availability and uptake

Submergence results in increased solution-K concentration and enhanced K diffusion to rice roots, particularly on soils with a small K-fixation potential (e.g., soils containing predominantly 1:1 layer kaolinitic clay minerals).

Flooding of dry lowland rice soils containing 2:1 layer clay minerals may increase K fixation and reduce the solution concentration so that rice depends on nonexchangeable reserves for K supply.

General K management

K management should be considered part of long-term soil fertility management because K is not easily lost from or added to the root zone by the short-term biological and chemical processes that affect the N supply.

K management must ensure that N-use efficiency is not constrained by K deficiency (see Section 1.8).

2.4 Zinc deficiency

Function and mobility of Zn

Zinc is essential for several biochemical processes in the rice plant. Zn accumulates in roots but can be translocated from roots to developing plant parts. Because little retranslocation of Zn occurs within the leaf canopy, particularly in N-deficient plants, Zn-deficiency symptoms are more common on younger leaves.

Zn-deficiency symptoms and effects on growth

Dusty brown spots on upper leaves of stunted plants appearing 2–4 weeks after transplanting (Annex A-10, A-19).

Growth is patchy and plants are stunted.

Deficiency in soil

Critical soil levels for occurrence of Zn deficiency:

- 0.6 mg Zn per kg: 1N NH_4-acetate, pH 4.8
- 1.0 mg Zn per kg: 0.05N HCl
- 2.0 mg Zn per kg: 0.1N HCl

Causes of Zn deficiency

- Small amount of available Zn in the soil.
- Planted varieties are susceptible to Zn deficiency (e.g., IR26).
- High pH (≥7 under anaerobic conditions).
- High HCO_3^- concentration because of reducing conditions in calcareous soils with high organic matter content or because of large concentrations of HCO_3^- in irrigation water.
- Depressed Zn uptake because of an increase in the availability of Fe, Ca, Mg, Cu, Mn, and P after flooding.

- Immobilization of Zn following large applications of P fertilizer (P-induced Zn deficiency).
- High P content in irrigation water (only in areas with polluted water).
- Large applications of organic manures and crop residues.
- Excessive liming.

Occurrence of Zn deficiency

- Intensively cropped soils where large amounts of N, P, and K fertilizers (which do not contain Zn) have been applied in the past.
- Triple-rice crop systems.

Soils particularly prone to Zn deficiency

- Leached, old acid-sulfate, sodic, saline-neutral, calcareous, peat, sandy, highly weathered, acid, and coarse-textured soils.
- Soils with high available P and Si status.

Effect of submergence on Zn availability and uptake

Under flooded conditions, Zn availability decreases because of the decrease in Zn solubility as pH increases.

Preventive strategies for Zn management

- *Varieties:* Select Zn-efficient varieties.
- *Crop establishment:* Dip seedlings or presoak seeds in a 2–4% ZnO suspension (e.g., 20–40 g ZnO per L of water).
- *Fertilizer management:* Apply organic manure. Apply 5–10 kg Zn per ha as Zn sulfate, Zn oxide, or Zn chloride as a prophylactic, either incorporated in the soil before seeding or transplanting, or applied to the nursery seedbed a few days before transplanting. On most soils, blanket applications of $ZnSO_4$ should be made every 2–8 crops.

- *Water management:* Drain triple-cropped land periodically. Do not use high pH (>8) water for irrigation.

Treatment of Zn deficiency

Zn deficiencies are most effectively corrected by soil Zn application. *Surface application is more effective than soil incorporation on high-pH soils.* Zn sulfate is the most commonly used Zn source (but ZnO is less costly). The following measures, either separately or in combination, are effective but should be implemented immediately at the onset of symptoms:

- If Zn-deficiency symptoms are observed in the field, broadcast 10–25 kg $ZnSO_4 \cdot H_2O$ or 20–40 kg $ZnSO_4 \cdot 7H_2O$ per ha over the soil surface. Mix the Zn sulfate (25%) with sand (75%) for a more even application.
- Apply 0.5–1.5 kg Zn per ha as a foliar spray (e.g., a 0.5% $ZnSO_4$ solution at about 200 L water per ha) for emergency treatment of Zn deficiency in growing plants.

2.5 Sulfur deficiency

Function and mobility of S

Sulfur is required for protein synthesis, plant function, and plant structure. S is also involved in carbohydrate metabolism. It is less mobile in the plant than N so that deficiency tends to appear first on young leaves.

S-deficiency symptoms and effect on growth

Pale green plants, light green-colored young leaves (Annex A-10, A-21).

Deficiency in soil

S deficiency is sometimes confused with N-deficiency symptoms. Soil tests for S are not reliable unless they include inorganic S as well as some of the mineralizable organic S fraction (ester sulfates).

The critical soil levels for occurrence of S deficiency:

- <5 mg S per kg: 0.05 M HCl,
- <6 mg S per kg: 0.25 M KCl heated at 40 ºC for 3 hours, and
- <9 mg S per kg: 0.01 M $Ca(H_2PO_4)_2$.

Causes of S deficiency

- Low available S content in the soil.
- Depletion of soil S as a result of intensive cropping.
- Use of S-free fertilizers (e.g., urea substituted for ammonium sulfate, triple superphosphate substituted for single superphosphate, and muriate of potash substituted for sulfate of potash).

- In many rural areas of developing countries, the amount of S deposition in precipitation is small because of the low levels of industrial gas emission.
- Sulfur concentrations in groundwater, however, may range widely. Irrigation water usually contains only small quantities of SO_4^{2-}.
- S contained in organic residues is lost during burning.

Soils particularly prone to S deficiency

- Soils containing allophane (e.g., Andisols).
- Soils with low organic matter status.
- Highly weathered soils containing large amounts of Fe oxides.
- Sandy soils, which are easily leached.

Occurrence of S deficiency

- S deficiency is less common in rice production areas located near industrial centers where gas emission is great.

Effect of submergence on S availability and uptake

S availability decreases under submerged conditions.

Preventive strategies for S management

On most lowland soils, S supply from natural sources or S-containing fertilizer is similar to or exceeds the amount of S removed in rice grain.

S deficiency is easily corrected or prevented by using S-containing fertilizers.

- *Natural inputs:* Estimate the amount of S inputs from atmospheric deposition.

- *Nursery:* Apply S to the seedbed (rice nursery) in the form of S-containing fertilizers (ammonium sulfate, single superphosphate).
- *Fertilizer management:* Replenish S removed in crop parts by applying N and P fertilizers that contain S (e.g., ammonium sulfate [24% S], single superphosphate [12% S]). This can be done at irregular intervals.
- *Straw management:* Incorporate straw instead of removing or burning it. About 40–60% of the S contained in straw is lost on burning.
- *Soil management:* Improve soil management to enhance S uptake:
  - maintain sufficient percolation (about 5 mm/day) to avoid excessive soil reduction or
  - carry out dry tillage after harvesting to increase the rate of sulfide oxidation during the fallow period.

Treatment of S deficiency

If S deficiency is identified during early growth, the response to S fertilizer is rapid and recovery from S deficiency symptoms can occur within 5 days of S fertilizer application.

- Where moderate S deficiency is observed, apply 10 kg S per ha.
- On soils with severe S deficiency, apply 20–40 kg S per ha.

2.6 Silicon deficiency

Function and mobility of Si

Silicon is a “beneficial” nutrient for rice. It is required for the development of strong leaves, stems, and roots. Water-use efficiency is reduced in Si-deficient plants because of increased transpiration losses.

Si-deficiency symptoms and effects on growth

Soft, droopy leaves and culms (Annex A-11, A-23).

Si-deficient plants are particularly susceptible to lodging.

Soil

The critical soil concentration for occurrence of Si deficiency is 40 mg Si per kg (1 M sodium acetate buffered at pH 4).

Causes of Si deficiency

- Low Si-supplying power because the soil is very “old” and strongly weathered.
- Parent material contains small amounts of Si.
- Removal of rice straw over long periods of intensive cropping results in the depletion of available soil Si.

Occurrence of Si deficiency

Si deficiency is not yet common in the intensive irrigated rice systems of tropical Asia.

Soils particularly prone to Si deficiency

- Old, degraded paddy soils in temperate or subtropical climates.
- Organic soils with small mineral Si reserves.
- Highly weathered and leached tropical soils.

Effect of submergence on Si availability and uptake

The amount of plant available Si increases after submergence.

Preventive strategies for Si management

- *Natural inputs:* Substantial inputs of Si from irrigation water occur in some areas, particularly if groundwater from landscapes with volcanic geology is used for irrigation.
- *Straw management:* In the long term, Si deficiency is prevented by not removing the straw from the field following harvest. Recycle rice straw (5–6% Si) and rice husks (10% Si).
- *Fertilizer management:* Avoid applying excessive amounts of N fertilizer in the absence of sufficient P + K.

Treatment of Si deficiency

Apply calcium silicate slag regularly to degraded paddy soils or peat soils, at a rate of 1–3 t/ha.

Apply granular silicate fertilizers for more rapid correction of Si deficiency:

- Calcium silicate: 120–200 kg/ha
- Potassium silicate: 40–60 kg/ha

2.7 Magnesium deficiency

Function and mobility of Mg

Magnesium is a constituent of chlorophyll and is involved in photosynthesis. Mg is very mobile and is retranslocated readily from old leaves to young leaves. Deficiency symptoms therefore tend to occur initially in older leaves.

Mg-deficiency symptoms and effects on growth

Orange-yellow interveinal chlorosis on older leaves (Annex A-10, A-25).

Soil

A concentration of <1 $cmol_c$ Mg per kg soil indicates very low soil Mg status. Concentrations of >3 $cmol_c$ Mg per kg are generally sufficient for rice.

Causes of Mg deficiency

- Low available soil Mg.
- Decreased Mg uptake because of a wide ratio of exchangeable K:Mg (i.e., >1:1).

Occurrence of Mg deficiency

Mg deficiency is not frequently observed in the field because adequate amounts are usually supplied in irrigation water. Mg deficiency is more common in rainfed lowland and upland rice, where soil Mg has been depleted as a result of the continuous removal of Mg in crop products.

Soils particularly prone to Mg deficiency

- Acid, low-CEC soils in uplands and lowlands.
- Coarse-textured sandy soils with high percolation rates and leaching losses.

- Leached, old acid-sulfate soils with low base content.

Effect of submergence on Mg availability and uptake

The concentration of Mg in the soil solution tends to increase after flooding.

Preventive strategies for Mg management

- *Crop management:* Apply sufficient amounts of Mg fertilizer, farmyard manure, or other materials to balance removal in crop products and straw.
- *Water management:* Minimize percolation rates (leaching losses) on coarse-textured soils by compacting the subsoil during land preparation.
- *Soil management:* Minimize losses from erosion and surface runoff in upland systems by using appropriate soil conservation measures.

Treatment of Mg deficiency

Mg deficiency should be treated as follows:

- Apply Mg-containing fertilizers. Rapid correction of Mg-deficiency symptoms is achieved by applying a soluble Mg source such as kieserite, langbeinite, or Mg chloride.
- Foliar application of liquid fertilizers containing Mg (e.g., $MgCl_2$).
- On acid upland soils, apply dolomite to supply Mg and increase soil pH (to alleviate Al toxicity; Section 2.17).

2.8 Calcium deficiency

Function and mobility of Ca

Deficiency symptoms usually appear first on young leaves. Ca deficiency also results in impaired root function and may predispose the rice plant to Fe toxicity (Section 2.13).

An adequate supply of Ca increases resistance to diseases such as bacterial leaf blight or brown spot.

Ca-deficiency symptoms and effects on growth

Chlorotic-necrotic split or rolled tips of younger leaves (Annex A-11, A-27).

Soil

Ca deficiency is likely when soil exchangeable Ca is <1 $cmol_c$/kg, or when the Ca saturation is <8% of the CEC. For optimum growth, Ca saturation of the CEC should be >20%.

Also for optimum growth, the ratio of Ca:Mg should be 3–4:1 for exchangeable soil forms and 1:1 in soil solution.

Causes of Ca deficiency

- Small amounts of available Ca in soil (degraded, acid, sandy soils).
- Alkaline pH with a wide exchangeable Na:Ca ratio, resulting in reduced Ca uptake.
- Wide soil Fe:Ca or Mg:Ca ratios, resulting in reduced Ca uptake.
- Excessive N or K fertilizer application, resulting in wide NH_4:Ca or K:Ca ratios and reduced Ca uptake.
- Excessive P fertilizer application, which may depress the availability of Ca (because of the formation of Ca phosphates in alkaline soils).

Occurrence of Ca deficiency

Ca deficiency is very uncommon in lowland rice soils because there is usually sufficient Ca in the soil, from mineral fertilizer applications and irrigation water.

Soils particularly prone to Ca deficiency

- Acid, strongly leached, low-CEC soils in uplands and lowlands.
- Soils derived from serpentine rocks.
- Sandy soils with high percolation rates and leaching.
- Leached, old acid-sulfate soils with low base content.

Effect of submergence on Ca availability and uptake

The concentration of Ca in the soil solution tends to increase after submergence.

Preventive strategies for Ca management

- *Crop management:* Apply farmyard manure or straw (incorporated or burned) to balance Ca removal in soils containing small concentrations of Ca.
- *Fertilizer management:* Use single superphosphate (13–20% Ca) or triple superphosphate (9–14% Ca) as a P source.

Treatment of Ca deficiency

Ca deficiency should be treated as follows:

- Apply $CaCl_2$ (solid or in solution) or Ca-containing foliar sprays for rapid treatment of severe Ca deficiency.
- Apply gypsum on Ca-deficient high-pH soils (e.g., on sodic and high-K soils).
- Apply lime on acid soils to increase pH and Ca availability.
- Apply Mg or K in conjunction with Ca because Ca may induce deficiency of these nutrients.
- Apply pyrites to mitigate the inhibitory effects of $NaHCO_3$-rich water on Ca uptake.

2.9 Iron deficiency

Function and mobility of Fe

Iron is required for photosynthesis. Fe deficiency may inhibit K absorption. Because Fe is not mobile within rice plants, young leaves are affected first.

Fe-deficiency symptoms and effects on growth

Interveinal yellowing and chlorosis of emerging leaves (Annex A-11, A-29).

Soil

Fe deficiency is likely when soil Fe concentration is either

- <2 mg Fe per kg: NH_4-acetate, pH 4.8, or
- <4–5 mg Fe per kg: DTPA-$CaCl_2$, pH 7.3.

Causes of Fe deficiency

- Low concentration of soluble Fe^{2+} in upland soils.
- Insufficient soil reduction under submerged conditions (e.g., low organic matter status soils).
- High pH of alkaline or calcareous soils following submergence (i.e., decreased solubility and uptake of Fe because of large bicarbonate concentrations).
- Wide P:Fe ratio in the soil (i.e., Fe bound in Fe phosphates, possibly because of the excessive application of P fertilizer).

Occurrence of Fe deficiency

- Neutral, calcareous, and alkaline upland soils.
- Alkaline and calcareous lowland soils with low organic matter status.
- Lowland soils irrigated with alkaline irrigation water.
- Coarse-textured soils derived from granite.

Effect of submergence on Fe availability and uptake

Fe availability increases after flooding. Solubility of Fe increases when Fe^{3+} is reduced to the more soluble Fe^{2+} during organic matter decomposition. In flooded soils, Fe deficiency may occur when organic matter decomposition is insufficient to drive the reduction of Fe^{3+} to Fe^{2+}.

Preventive strategies for Fe management

- *Varieties:* Selection of high-Fe rice cultivars is in progress to improve human Fe nutrition.
- *Soil management:* Apply organic matter (e.g., crop residues, animal manure).
- *Fertilizer management:* Use acidifying fertilizers (e.g., ammonium sulfate instead of urea) on high-pH soils. Use fertilizers containing Fe as a trace element.

Treatment of Fe deficiency

Fe deficiency is the most difficult and costly micronutrient deficiency to correct. Soil applications of inorganic Fe sources are often ineffective in controlling Fe deficiency, except when application rates are large. Fe deficiency should be treated as follows:

- Apply solid $FeSO_4$ (about 30 kg Fe per ha) next to rice rows, or broadcast (larger application rate required).
- Foliar applications of $FeSO_4$ (2–3% solution) or Fe chelates. Because of low Fe mobility in the plant, 2–3 applications at 2-week intervals (starting at tillering) are necessary to support new plant growth.

2.10 Manganese deficiency

Function and mobility of Mn

Manganese is required for photosynthesis. Mn accumulates in roots before it moves to aboveground shoots. There is some translocation of Mn from old to young leaves.

Mn-deficiency symptoms and effects on growth

Interveinal chlorosis starting at the tip of younger leaves (Annex A-11, A-31).

Soil

Critical soil levels for occurrence of Mn deficiency:

- 1 mg Mn per kg, terephthalic acid + $CaCl_2$, pH 7.3.
- 12 mg Mn per kg, 1N NH_4-acetate + 0.2% hydroquinone, pH 7.

Causes of Mn deficiency

- Small available Mn content in soil.
- Fe-induced Mn deficiency because of a large concentration of Fe in soil.
- Reduced Mn uptake because of large concentrations of Ca^{2+}, Mg^{2+}, Zn^{2+}, or NH_4^+ in soil solution.
- Excessive liming of acid soils.
- Reduced Mn uptake because of hydrogen sulfide accumulation.

Occurrence of Mn deficiency

Mn deficiency occurs frequently in upland rice, but is uncommon in rainfed or lowland rice because the solubility of Mn increases under submerged conditions.

Soils particularly prone to Mn deficiency

- Acid upland soils (Ultisols, Oxisols).
- Alkaline and calcareous soils with low organic matter status and small amounts of reducible Mn.
- Degraded paddy soils containing large amounts of active Fe.
- Leached, sandy soils containing small amounts of Mn.
- Leached, old acid-sulfate soils with low base content.
- Alkaline and calcareous organic soils (Histosols).
- Highly weathered soils with low total Mn content.

Effect of submergence on Mn availability and uptake

Mn availability increases with flooding as Mn^{4+} is reduced to the more plant-available Mn^{2+}.

Preventive strategies for Mn management

- *Crop management:* Apply farmyard manure or straw (incorporated or burned).
- *Fertilizer management:* Use acid-forming fertilizers, such as ammonia sulfate, $(NH_4)_2SO_4$, instead of urea.

Treatment of Mn deficiency

Mn deficiencies can be corrected by foliar application of Mn or by banding Mn with an acidifying starter fertilizer. Mn deficiency should be treated as follows:

- Apply $MnSO_4$ or finely ground MnO (5–20 kg Mn per ha) in bands along rice rows.
- Apply foliar $MnSO_4$ for rapid treatment of Mn deficiency (1–5 kg Mn per ha in about 200 L water per ha).
- Chelates are less effective because Fe and Cu displace Mn.

2.11 Copper deficiency

Function and mobility of Cu

Copper plays a key role in the following processes:

- N, protein, and hormone metabolism.
- Photosynthesis and respiration.
- Pollen formation and fertilization.

The mobility of Cu in rice plants depends partly on leaf N status; little retranslocation of Cu occurs in N-deficient plants. Cu-deficiency symptoms are more common on young leaves.

Cu-deficiency symptoms and effects on growth

Chlorotic streaks, bluish green leaves, which become chlorotic near the tips (Annex A-11, A-33).

Soil

Critical soil levels for occurrence of Cu deficiency:

- 0.1 mg Cu per kg, 0.05N HCl, or
- 0.2–0.3 mg Cu per kg, DTPA + $CaCl_2$, pH 7.3.

Causes of Cu deficiency

- Small amount of available Cu in soil.
- Strong adsorption of Cu on humic and fulvic acids (peat soils).
- Small amounts of Cu in parent materials (sandy soils derived from quartz).
- Large NPK fertilizer application rates, resulting in rapid plant growth rates and exhaustion of Cu in soil solution.
- Overliming of acid soils.
- Excessive Zn in the soil, inhibiting Cu uptake.

Occurrence of Cu deficiency

- High organic matter status soils (Histosols, humic volcanic ash soils, peat soils).
- Lateritic, highly weathered soils (Ultisols, Oxisols).
- Soils derived from marine sediments (limestone).
- Sandy-textured soils, calcareous soils.

Effect of submergence on Cu availability and uptake

The availability of Cu decreases at flooding.

Preventive strategies for Cu management

- *Crop management:* Dip seedling roots in 1% $CuSO_4$ suspensions for an hour before transplanting.
- *Soil management:* Avoid overliming of acid soils because it may reduce Cu uptake.
- *Fertilizer management:* On Cu-deficient soils, apply CuO or $CuSO_4$ (5–10 kg Cu per ha at 5-year intervals) for long-term maintenance of soil Cu (broadcast and incorporate in soil).

Treatment of Cu deficiency

- Apply $CuSO_4$ (solid or liquid form) for rapid treatment of Cu deficiency (about 1–5 kg Cu per ha). For soil application, fine $CuSO_4$ material is either broadcast (or banded) on the soil or incorporated as a basal application.
- Foliar Cu can be applied during tillering to panicle initiation, but may cause leaf burn in growing tissues.
- Avoid applying excessive Cu because the range between Cu deficiency and toxicity is narrow.

2.12 Boron deficiency

Function and mobility of B

Boron is an important constituent of cell walls. B deficiency results in reduced pollen viability.

Because B is not retranslocated to new growth, deficiency symptoms usually appear first on young leaves.

B-deficiency symptoms and effects on growth

White, rolled leaf tips of young leaves (Annex A-11).

Soil

The critical soil level for occurrence of B deficiency is 0.5 mg B per kg hot water extraction.

Causes of B deficiency

- Small amount of available B in soil.
- B adsorption on organic matter, clay minerals, and sequioxides.
- Reduction in B mobility because of drought.
- Excessive liming.

Occurrence of B deficiency

- Highly weathered, acid red soils and sandy rice soils.
- Acid soils derived from igneous rocks.
- High organic matter status soils.

Effect of submergence on B availability and uptake

When pH<6, B is present mostly as undissociated boric acid, $B(OH)_3$, and plant uptake depends on mass flow. When pH>6, $B(OH)_3$ is increasingly dissociated and hydrated to $B(OH)_4^-$ and uptake is actively regulated by

the plant. B adsorption to organic matter, sequioxides, and clay minerals increases with increasing pH. Therefore, after flooding, B availability decreases in acid soils and increases in alkaline soils.

Preventive strategies for B management

- *Water management:* Avoid excessive leaching (percolation). B is very mobile in flooded rice soils.
- *Fertilizer management:* On B-deficient soils, apply slow-acting B sources (e.g., colemanite) at intervals of 2–3 years.

Treatment of B deficiency

- Apply B in soluble forms (borax) for rapid treatment of B deficiency (0.5–3 kg B per ha), broadcast and incorporated before planting, topdressed, or as foliar spray during vegetative rice growth.
- Borax and fertilizer borates should not be mixed with ammonium fertilizers as this will cause NH_3 volatilization.

2.13 Iron toxicity

Mechanism of Fe toxicity

Iron toxicity is primarily caused by the toxic effects of excessive Fe uptake because of a large concentration of Fe in the soil solution. Recently transplanted rice seedlings may be affected when large amounts of Fe^{2+} accumulate immediately after flooding. In later growth stages, rice plants are affected by excessive Fe^{2+} uptake because of increased root permeability and enhanced microbial Fe reduction in the rhizosphere. Excessive Fe uptake results in leaf bronzing. Large amounts of Fe in plants can cause phytotoxicity. Fe toxicity is related to multiple nutritional stress, which leads to reduced root oxidation power. A black stain of Fe sulfide (a diagnostic indication of excessively reduced conditions and Fe toxicity) may then form on the root surface.

Fe-toxicity symptoms and effects on growth

Tiny brown spots on lower leaves starting from the tip or whole leaves colored orange-yellow to brown. Black coating on root surfaces (Annex A-35).

Plant

Fe content in affected plants is usually (but not always) high (300–2,000 mg Fe per kg), but the critical Fe content depends on plant age and general nutritional status. The critical threshold is lower in low fertility status soils in which nutrient supply is not properly balanced.

Effect of submergence on Fe toxicity

In most mineral soils, the concentration of Fe^{2+} peaks at 2–4 weeks following submergence. A large concentration of Fe^{2+} in the soil may retard K and P uptake. Under strongly reducing conditions, the production of H_2S and FeS may

contribute to Fe toxicity by reducing root oxidation power.

The oxidation of Fe^{2+} to Fe^{3+} because of the release of oxygen by rice roots causes acidification in the rice rhizosphere and the formation of a brownish coating on rice roots.

Causes of Fe toxicity

- A large Fe^{2+} concentration in the soil solution because of strongly reducing conditions in the soil and/or low pH.
- Low and unbalanced crop nutrient status. Poor root oxidation and Fe^{2+} exclusion power because of P, Ca, Mg, or K deficiency.
- Poor Fe^{2+} exclusion power because of the accumulation in the rhizosphere of substances that inhibit respiration, such as organic acids, H_2S, and FeS (Section 2.14).
- Application of large amounts of undecomposed organic residues.
- Continuous supply of Fe into soil from groundwater or lateral seepage from hills.
- Application of urban or industrial sewage with a high Fe content.

Occurrence of Fe toxicity

Fe toxicity occurs on a wide range of soils, but generally in lowland rice soils with permanent flooding during crop growth. Common features of Fe-toxic sites are poor drainage and low soil CEC and macronutrient content, but Fe toxicity occurs over a wide range of soil pH (4–7). Soils prone to Fe toxicity are

- Poorly drained soils (Aquents, Aquepts, Aquults) in inland valleys receiving inflow from acid upland soils.
- Kaolinitic soils with low CEC and little available P and K.
- Alluvial or colluvial acid clayey soils.
- Young acid-sulfate soils.
- Acid lowland or highland peat soils.

Preventive strategies for Fe toxicity management

- *Varieties:* Plant rice varieties tolerant of Fe toxicity (e.g., IR8192-200, IR9764-45, Kuatik Putih, Mahsuri).
- *Seed treatment:* In temperate climates where direct seeding is practiced, coat seeds with oxidants (e.g., Ca peroxide at 50–100% of seed weight) to improve germination and seedling emergence by increasing the O_2 supply.
- *Crop management:* Delay planting until the peak in Fe^{2+} concentration has passed (i.e., not less than 10–20 days after flooding).
- *Water management:* Use intermittent irrigation and avoid continuous flooding on poorly drained soils containing a large concentration of Fe and organic matter.
- *Fertilizer management:* Balance the use of fertilizers (NPK or NPK + lime) to avoid nutrient stress. Apply lime on acid soils. Do not apply excessive amounts of organic matter (manure, straw) on soils containing large amounts of Fe and organic matter or where drainage is poor.
- *Soil management:* Carry out dry tillage after the rice harvest to increase Fe oxidation during the fallow period.

Treatment of Fe toxicity

Preventive management strategies should be followed because treatment of Fe toxicity during crop growth is difficult. Options for treatment of Fe toxicity:

- Apply additional K, P, and Mg fertilizers.
- Incorporate lime in the topsoil to raise pH in acid soils.
- Incorporate about 100–200 kg MnO_2 per ha in the topsoil to decrease Fe^{3+} reduction.
- Carry out midseason drainage to remove accumulated Fe^{2+}. At the midtillering stage (25–30 DAT/DAS), drain the field and keep it free of floodwater (but moist) for about 7–10 days to improve oxygen supply during tillering.

2.14 Sulfide toxicity

Mechanism of sulfide toxicity

An excessive concentration of hydrogen sulfide in the soil results in reduced nutrient uptake because of a decrease in root respiration. Hydrogen sulfide has an adverse effect on metabolism when an excessive amount is taken up by the rice plant.

Rice roots release O_2 to oxidize H_2S in the rhizosphere. H_2S toxicity therefore depends on the strength of root oxidizing power, H_2S concentration in the soil solution, and root health as affected by nutrient supply. Young rice plants are particularly susceptible to sulfide toxicity before the development of oxidizing conditions in the rhizosphere. Physiological disorders attributed to H_2S toxicity include Akiochi in Japan and straighthead in the southern United States.

Sulfide-toxicity symptoms and effects on growth

Interveinal chlorosis of emerging leaves. Coarse, sparse, and blackened roots (Annex A-37).

Leaf symptoms of sulfide toxicity are similar to those of chlorosis caused by Fe deficiency (Section 2.9). Other diagnostic criteria are similar to those of Fe toxicity (but Fe toxicity has different visual leaf deficiency symptoms, Section 2.13):

- Coarse, sparse, dark brown to black root system. Freshly uprooted rice hills often have poorly developed root systems with many black roots (stains of Fe sulfide). In contrast, healthy roots are covered with a uniform and smooth orange-brown coating of Fe^{3+} oxides and hydroxides.
- Small concentration of K, Mg, Ca, Mn, and Si content in plant tissue.

Normal ranges and critical levels for occurrence of sulfide toxicity

No critical levels have been established. Sulfide toxicity depends on the concentration of sulfide in the soil solution relative to the oxidation power of rice roots. H_2S toxicity can occur when the concentration of H_2S is >0.07 mg per L in the soil solution.

Effect of submergence on sulfide toxicity

The reduction of sulfate to sulfide in flooded soils has three implications for rice culture:

- S may become deficient,
- Fe, Zn, and Cu may become immobilized, and
- H_2S toxicity may occur in soils containing small amounts of Fe.

In submerged soils, sulfate is reduced to H_2S at low redox potential (<−50 mV at pH 7), which then forms insoluble sulfides such as FeS.

Fe sulfides are not toxic to rice, but they reduce nutrient uptake (Section 2.13).

Causes of sulfide toxicity

- A large concentration of H_2S in the soil solution (because of strongly reducing conditions and little precipitation of FeS).
- Poor and unbalanced crop nutrient status, causing reduced root oxidation power (because of deficiencies of K in particular but also of P, Ca, or Mg).
- Excessive application of sulfate in fertilizers or urban or industrial sewage on poorly drained, strongly reducing soils.

Soils prone to H_2S toxicity

- Well-drained sandy soils with low active Fe status.
- Degraded paddy soils with low active Fe status.
- Poorly drained organic soils.

- Acid-sulfate soils.

  Soils prone to sulfide toxicity and Fe toxicity are similar in containing a large amount of active Fe, small CEC, and small concentration of exchangeable bases.

Preventive strategies for sulfide toxicity management

- *Varieties:* Grow rice varieties that tolerate sulfide toxicity because of their greater capacity to release O_2 from roots.
- *Seed treatment:* In temperate climates, coat seeds with oxidants (e.g., Ca peroxide) to increase the O_2 supply at seed germination.
- *Water management:* Avoid continuous flooding and use intermittent irrigation in soils that contain large concentrations of S, have high organic matter status, and are poorly drained.
- *Fertilizer management:* Balance the use of fertilizer nutrients (NPK or NPK + lime) to avoid nutrient stress and improve root oxidation power. Apply sufficient K fertilizer (Section 2.3). Avoid using excessive amounts of organic residues (manure, straw) in soils containing large amounts of Fe and organic matter, and in poorly drained soils.
- *Soil management:* Carry out dry tillage after harvest to increase S and Fe oxidation during the fallow period.

Treatment of sulfide toxicity

- Apply K, P, and Mg fertilizers.
- Apply Fe (salts, oxides) on low-Fe soils to increase immobilization of H_2S as FeS.
- Carry out midseason drainage to remove accumulated H_2S and Fe^{2+}. Drain the field at the midtillering stage (25–30 DAT/DAS), and maintain floodwater-free (but moist) conditions for about 7–10 days to improve oxygen supply during tillering.

2.15 Boron toxicity

Mechanism of B toxicity

When the B concentration in the soil solution is large, B is distributed throughout the plant following water movement driven by transpiration, causing the accumulation of B in leaf margins and leaf tips. Excess B appears to inhibit the formation of starch from sugars or results in the formation of B-carbohydrate complexes, resulting in retarded grain filling but normal vegetative growth.

B-toxicity symptoms and effects on growth

Brownish leaf tips and dark brown elliptical spots on leaves (Annex A-39).

Plant

- There is a steep concentration gradient of B within a leaf blade, from low values at the leaf base to high values at the leaf tip.
- Critical toxicity levels in field-grown rice are lower than those of plants grown in the greenhouse because B is leached from leaves under open conditions during rainfall.
- The effect on yield differs significantly among rice varieties.

Soil

Critical toxicity limits of B in the soil:

- >4 mg B per kg: 0.05N HCl.
- >5 mg B per kg: hot-water soluble B.
- >2.5 mg B per L: soil solution.

Irrigation water

B concentration of >2 mg B per L may cause B toxicity.

Effect of submergence on B toxicity

- Flooding acid soils decreases B availability.

- Flooding alkaline soils increases B availability.

Causes of B toxicity

- A large B concentration in the soil solution because of the use of B-rich groundwater and high temperature.
- A large B concentration in the soil solution because of B-rich parent material. B content is large in some marine sediments, plutonic rocks, and other volcanic materials.
- Excess application of borax or municipal waste.

Occurrence of B toxicity

B toxicity is most common in arid and semiarid regions, but has also been reported in rice in other areas.

Soils prone to B toxicity

- Soils formed on volcanic parent material, usually associated with the use of irrigation water pumped from deep wells containing a large B concentration.
- Some coastal saline soils.

Preventive strategies for B toxicity management

- *Varieties:* Plant B-toxicity-tolerant varieties (e.g., IR42, IR46, IR48, IR54, IR9884-54).
- *Water management:* Use surface water with a low B content for irrigation. Groundwater must be monitored regularly if used for irrigation. If the B concentration is too great, dilute with uncontaminated water.
- *Soil management:* Plow when the soil is dry so that B accumulates in the topsoil. Then leach with water containing a small amount of B.

Treatment of B toxicity

Leach with low-B irrigation water if percolation is sufficient and a suitable water source is available.

2.16 Manganese toxicity

Mechanism of Mn toxicity

Manganese concentration in the soil solution can increase at low soil pH or when the redox potential is low after flooding. Excessive amounts of Mn in the soil solution can lead to excess Mn uptake when exclusion or tolerance mechanisms in roots are not functioning adequately. A large concentration of Mn in plant tissue changes metabolic processes (e.g., enzyme activities and organic compounds) that lead to visible Mn-toxicity symptoms such as chlorosis or necrosis.

Mn-toxicity symptoms and effects on growth

Yellowish brown spots between leaf veins, extending to the whole interveinal area (Annex A-41).

Effect of submergence on Mn toxicity

Flooding affects Mn toxicity in rice because of

- Increased Mn solubility with decreasing redox potential.
- Reduced Mn oxidation by roots because of a lack of oxygen.

Causes of Mn toxicity

Mn toxicity can be caused by

- A large concentration of Mn^{2+} in the soil solution because of low soil pH (<5.5) and/or low redox potential.
- Poor and unbalanced crop nutrient status.
- Poor root oxidation and Fe^{2+}-excluding power because of
  - deficiencies of Si, K, P, Ca, or Mg, and
  - substances that inhibit respiration (e.g., organic acids, H_2S, and FeS) (Section 2.14).
- Application of urban or industrial waste with large Mn content.

Occurrence of Mn toxicity

Mn toxicity rarely occurs in lowland rice. Despite large Mn concentrations in solution, Mn toxicity is uncommon because rice is comparatively tolerant of large Mn concentrations. Rice roots are able to exclude Mn and rice has a high internal tolerance for large tissue-Mn concentrations. Soils where Mn toxicity can occur are as follows:

- Acid, upland soils (pH<5.5), in which Mn toxicity often occurs together with Al toxicity (Section 2.17); lowland soils containing large amounts of easily reducible Mn; and acid-sulfate soils.
- Areas affected by Mn mining (e.g., Japan).

Preventive strategies for Mn toxicity management

- Seed treatment: In a temperate climate, coat seeds with oxidants (e.g., Ca peroxide) to improve germination and seedling emergence by increasing the supply of O_2.
- Water management: Mn absorption may be increased when surface drainage is practiced.
- Fertilizer management: Balance the use of fertilizers (NPK or NPK + lime) to avoid nutrient stress as a source of Mn toxicity. Apply lime on acid soils to reduce the concentration of active Mn. Do not apply excessive amounts of organic matter (manure, straw) on soils containing large concentrations of Mn and organic matter, and on poorly drained soils.
- Straw management: Recycle straw or ash to replenish Si and K removed from the field. An adequate Si supply prevents Mn toxicity of rice plants by decreasing plant Mn uptake (increased root oxidation) and by increasing the internal tolerance for an excessive amount of Mn in plant tissue.

Treatment of Mn toxicity

- Apply lime to alleviate soil acidity in upland soils.
- Apply silica slags (1.5–3 t/ha) to alleviate Si deficiency (Section 2.6).

2.17 Aluminum toxicity

Mechanism of Al toxicity

The most important symptom of Al toxicity is the inhibition of root growth. Long-term exposure of plants to Al also inhibits shoot growth by inducing nutrient (Mg, Ca, P) deficiencies and drought stress.

Al-toxicity symptoms and effects on growth

Orange-yellow interveinal chlorosis on leaves. Poor root growth, stunted plants (Annex A-43).

Soil

Al saturation of >30%, soil pH (H_2O) <5.0, and >1–2 mg Al per L in the soil solution indicate potential Al toxicity.

Effect of submergence on Al toxicity

Al toxicity is a major constraint in upland soils under aerobic and acid soil conditions. Upon flooding, soil pH increases and Al concentration in the soil solution decreases and generally falls below the critical level for Al toxicity. Under such conditions, Fe toxicity (Section 2.13) is more likely to occur than Al toxicity.

Causes of Al toxicity

Excess Al^{3+} concentration in the soil solution is caused by low soil pH (<5). The concentration of Al in the soil solution depends on soil pH as well as the concentration of organic and inorganic compounds that can form complexes with Al.

Occurrence of Al toxicity

Al toxicity rarely occurs in lowland rice except in some soils where soil reduction after flooding proceeds very slowly. Al toxicity occurs on the following soils:

- acid, upland soils (Ultisols, Oxisols) with large exchangeable Al content. Al toxicity often occurs together with Mn toxicity (Section 2.16);
- acid-sulfate soils, particularly when rice is grown as an upland crop for a few weeks before flooding; and
- flooded soils with pH<4 before Fe-toxicity symptoms appear.

Preventive strategies for Al-toxicity management

- *Varieties:* Plant Al-tolerant cultivars, such as IR43, CO 37, and Basmati 370 (India), Agulha Arroz, Vermelho, and IAC3 (Brazil), IRAT 109 (Côte d'Ivoire), and Dinorado (Philippines).
- *Crop management:* Delay planting until pH has increased sufficiently after flooding (to immobilize Al).
- Water management: Provide crops with sufficient water to maintain reduced soil conditions. Prevent the topsoil from drying out.
- *Fertilizer management:* On acid upland soils with Al toxicity, pay special attention to Mg fertilization (Section 2.7). Liming with $CaCO_3$ may not be sufficient, whereas the application of dolomite instead of $CaCO_3$ not only raises the pH but also supplies Mg. Small amounts of kieserite and langbeinite (50 kg per ha) may have an effect similar to that of liming with more than 1,000 kg $CaCO_3$.

Treatment of Al toxicity

- Apply 1–3 t lime per ha to raise pH.
- Ameliorate subsoil acidity to improve root growth below the plow layer by leaching Ca into the subsoil from lime applied to the soil surface.
- On acid, upland soils, install soil erosion traps and incorporate 1 t/ha of reactive rock phosphate to alleviate P deficiency (Section 2.2).

2.18 Salinity

Mechanism of salinity injury

Salinity is defined as the presence of excessive amounts of soluble salts in the soil. Na, Ca, Mg, chloride, and sulfate are the major ions involved. The effects of salinity on rice growth are

- osmotic effects (water stress),
- toxic ionic effects of excess Na and Cl uptake, and
- a reduction in nutrient uptake (K, Ca) because of antagonistic effects.

Rice tolerates salinity during germination, is very sensitive during early growth (1–2-leaf stage), is tolerant during tillering and elongation, but becomes sensitive again at flowering.

Salinity symptoms and effects on growth

White leaf tips and stunted, patchy growth in the field (Annex A-45).

Further effects on rice growth include

- reduced germination rate,
- reduced plant height and tillering,
- poor root growth, and
- increased spikelet sterility.

Soil

For rice growing in flooded soil, EC is measured in the soil solution or in a saturation extract (EC_e). For upland rice grown at field capacity or below, EC in the soil solution is about twice as great as that of the saturation extract. Rough approximations of the yield decrease caused by salinity are

- EC_e <2 dS/m: optimum, no yield reduction
- EC_e >4 dS/m: slight yield reduction (10–15%)
- EC_e >6 dS/m: moderate reduction in growth and yield (20–50%)
- EC_e >10 dS/m: >50% yield reduction in susceptible cultivars

Exchangeable sodium percentage (ESP):

- ESP <20%: no significant yield reduction
- ESP >20–40%: slight yield reduction (10%)
- ESP >80%: 50% yield reduction

Sodium adsorption ratio (SAR):

- SAR >15: sodic soil (measured as cations in saturation extract)

Irrigation water

- pH 6.5–8, EC <0.5 dS/m: high quality
- pH 8–8.4, EC 0.5–2 dS/m: medium-to-poor
- pH >8.4, EC >2 dS/m: unsuitable for irrigation

- SAR <15: high quality, low Na
- SAR 15–25: medium-to-poor quality, high Na
- SAR >25: unsuitable for irrigation, very high Na

Effect of submergence on salinity

Submergence has two effects on salinity:

- An increase in EC because of the greater solubility of salts and the reduction of Fe and Mn from less soluble to soluble compounds.
- Continuous percolation of the soil because of irrigation. If the EC in the irrigation water exceeds that of the soil solution, the concentration of salt in the soil will increase.

Causes of salinity

Plant growth on saline soils is mainly affected by high levels of soluble salts (NaCl) causing ion toxicity, ionic imbalance, and impaired water balance. On sodic soils, plant growth is mainly affected by high pH and high HCO_3^- concentration.

Major causes of salinity or sodicity:

- Poor irrigation practice or insufficient irrigation water in seasons/years with low rainfall.
- High evaporation.
- An increase in the level of salinity in groundwater.
- Intrusion of saline seawater in coastal areas.

Occurrence of salinity

Salt-affected soils can be grouped into

- saline soils (EC >4 dS/m, ESP <15%, pH <8.5),
- saline-sodic soils (EC 4 dS/m, ESP >15%, pH about 8.5), and
- sodic soils (EC <4 dS/m, ESP >15%, pH >8.5, SAR >15).

Examples of salt-affected soils include

- saline coastal soils (widespread along coasts in many countries),
- saline acid-sulfate soils (e.g., Mekong Delta, Vietnam),
- neutral to alkaline saline, saline-sodic, and sodic inland soils (e.g., India, Pakistan, Bangladesh), and
- acid sandy saline soils (Korat region of northeast Thailand).

Preventive strategies for salinity management

Management of salinity or sodicity must include a combination of measures. Major choices include the following:

- *Cropping system:* In rice-upland crop systems, change to double-rice cropping if sufficient water is available and climate allows. After a saline soil is leached, a cropping pattern that includes rice and other salt-tolerant crops (e.g., legumes such as clover or Sesbania) must be followed for several years.
- *Varieties:* Grow salt-tolerant varieties (e.g., Pobbeli, Indonesia; IR2151, Vietnam; AC69-1, Sri Lanka; IR6, Pakistan; CSR10, India; Bicol, Philippines).
- *Water management:* Submerge the field for 2–4 weeks before planting rice. Do not use sodic irrigation water or alternate between sodic and nonsodic irrigation water sources. Leach the soil after planting under intermittent submergence to remove excess salts. Collect and store rainwater for irrigation of dry-season crops (e.g., by establishing reservoirs). In coastal areas, prevent intrusion of salt water.
- *Fertilizer management:* Apply Zn (5–10 kg Zn per ha) to alleviate Zn deficiency (Section 2.4). Apply sufficient N, P, and K. The application of K (Section 2.3) is important because it improves the K:Na, K:Mg, and K:Ca ratios in the plant. Use ammonium sulfate as an N source and apply N as topdressing at critical growth stages (Section 2.1) (basal N is less efficient on saline and sodic soils). In sodic soils, the replacement of Na by Ca (through the application of gypsum) may reduce P availability and result in an increased requirement for P fertilizer.
- *Organic matter management:* Organic amendments facilitate the reclamation of sodic soils by increasing partial CO_2 pressure and decreasing pH. Apply rice straw to recycle K. Apply farmyard manure.

Treatment of salinity

Options for treatment of salinity:

- Saline soils: Salinity can only be reduced by leaching with salt-free irrigation water. Because rice has a shallow root system, only the topsoil (0–20 cm) needs to be leached. Cost, availability of suitable water, and soil physical and hydraulic characteristics determine the feasibility of leaching. To reduce the level of salinity in affected soils, electrical conductivity in the irrigation water should be <0.5 dS/m). Where high-quality surface water is used (EC about 0), the amount of water required to reduce a given EC_e to a critical-level EC_c can be calculated as follows:

$$A_{iw} = A_{sat} [(EC_e / EC_c) + 1]$$

  where A_{iw} represents the amount of irrigation water (cm) added during irrigation and A_{sat} is the amount of water (cm) in the soil under saturated conditions.

  For example, to lower an initial EC_e of 16 dS/m to 4 dS/m in the top 20 cm of a clay loam soil (A_{sat} = 8–9 cm), about 40 cm of fresh water is required. Subsurface drains are required for leaching salts from clay-textured soils.

- Sodic soils: Apply gypsum ($CaSO_4$) to reduce Na saturation of the soil.

  Make a foliar application of K at the late tillering and panicle initiation stages, particularly if a low-tolerance variety is grown on saline soil.