
Chapter 5

Sources of plant nutrients and soil amendments

A large number of diverse materials can serve as sources of plant nutrients. These can be natural, synthetic, recycled wastes or a range of biological products including microbial inoculants. Except for microbial inoculants (biofertilizers), all of these contain one, two or several plant nutrients in readily or potentially available forms. A certain supply of mineral and organic nutrient sources is present in soils, but these often have to be supplemented with external applications for better plant growth. In practical farming, a vast variety of sources can find use in spite of large differences in their nature, nutrient contents, forms, physico-chemical properties and rate of nutrient release. These are not mutually exclusive but can be used together as components of INM.

Nutrient sources are generally classified as organic, mineral or biological. Organic nutrient sources are often described as manures, bulky organic manures or organic fertilizers. Most organic nutrient sources, including waste materials, have widely varying composition and often only a low concentration of nutrients, which differ in their availability. Some of these, such as cereal straw, release nutrients only slowly (owing to a wide C:N ratio) while others such as the N-rich leguminous green manures or oilcakes decompose rapidly and release nutrients quickly.

Residues from processed products of plant or animal origin are increasingly important as nutrient sources and lead to nutrient saving by recycling. In addition, a very wide range of products obtained from the recycling of crop, animal, human and industrial wastes can and do serve as sources of plant nutrient. A significant amount of N is made available through BNF by a number of micro-organisms in soils either independently or in symbiosis with certain plants. The inocula of such micro-organisms are commonly referred to as biofertilizers, which are used to enhance the N supply for crops.

The majority of nutrient input to agriculture comes from commercial mineral fertilizers. Organic manures are considered to play a significant but lesser role in nutrient contribution, leaving aside their beneficial effects on soil physico-chemical and biological properties. Such a conclusion could be due in part to inadequate data on the production and consumption of organic sources as compared with mineral fertilizers. Appreciable amounts of nutrients can also be brought in with rain (e.g. atmospheric deposition of nitrate and sulphate) and with irrigation water. This chapter describes common sources of plant nutrients. The last section deals with various soil amendments. Chapters 7 and 8 provide guidelines for the application of various nutrients through different sources.

MINERAL SOURCES OF NUTRIENTS (FERTILIZERS)

Definition, classification and general aspects

Definition

The term fertilizer is derived from the Latin word *fertilis*, which means fruit bearing. Fertilizer can be defined as a mined, refined or manufactured product containing one or more essential plant nutrients in available or potentially available forms and in commercially valuable amounts without carrying any harmful substance above permissible limits. Many prefixes such as synthetic, mineral, inorganic, artificial or chemical are often used to describe fertilizers and these are used interchangeably. Although organic fertilizers are also being prepared and used, they are not yet covered by the term fertilizers, largely owing to tradition and their generally much lower nutrient content. Strictly speaking, the most common mineral fertilizer, urea, is an organic compound that releases plant available N after transformation in the soil. In this section, the term fertilizer is used in a more narrow sense and widest acceptability.

Fertilizer grade is an expression used in extension and the fertilizer trade referring to the legal guarantee of the available plant nutrients expressed as a percentage by weight in a fertilizer, e.g. a 12–32–16 grade of NPK complex fertilizer indicates the presence of 12 percent nitrogen (N), 32 percent phosphorous pentoxide (P_2O_5) and 16 percent potash (K_2O) in it. On a fertilizer bag, the NPK content is always written in the sequence N, P_2O_5 and K_2O .

Synthetic fertilizers are sometimes referred to as being artificial or chemical fertilizers, implying that these are inferior to those termed natural (mainly organic) products. However, fertilizers are neither unnatural nor inferior products. Many fertilizers are finished products derived from natural deposits, either made more useful for plants (e.g. phosphate fertilizer) or separated from useless or even harmful components (e.g. K fertilizer). Although most N fertilizers are indeed produced artificially, i.e. synthesized in chemical factories, their N is derived from atmospheric air and their components such as nitrate, ammonia or urea are identical with the substances normally occurring in soils and plants. The primary source of all P in fertilizers is PR, a natural mineral that has to be mined, refined and solubilized in order to be useful.

Classification

Fertilizers have been traditionally classified as follows:

- Straight fertilizers: These contain one of the three major nutrients N, P or K. This is a traditional term referring to fertilizers that contain and are used for one major nutrient as opposed to multinutrient fertilizers. For secondary nutrients, these include products containing elemental S, magnesium sulphate, calcium oxide, etc. In the case of micronutrients, borax, Zn and Fe chelates and sulphate salts of micronutrients are straight fertilizers. However, the term is not often used for micronutrient carriers. This is not a very accurate term because many straight fertilizers also contain other essential plant nutrients, such as S in ammonium sulphate. These can also be termed single-nutrient

fertilizers. The term focuses on the most important nutrient for which a product was traditionally used disregarding other valuable constituents. In a strict sense, the term is justified only for products such as urea, ammonium nitrate (AN), and elemental S.

➤ Complex/compound fertilizers: These contain at least two out of the three major nutrients. They are produced by a chemical reaction between the raw materials containing the desired nutrients and they are generally solid granulated products. These include both two-nutrient (NP) and three-nutrient (NPK) fertilizers. These are also referred to as multinutrient fertilizers, but do not include fertilizer mixture or bulk blends as no chemical reaction is involved. The term is rarely used for multimicronutrient fertilizers or fortified fertilizers containing both macronutrients and micronutrients or for liquid fertilizers. The term multinutrient fertilizers is more appropriate as it includes both major nutrients and micronutrients. Moreover, it does not restrict itself to a particular production process. Multinutrient fertilizers can be further classified into: (i) complex/compound fertilizers; (ii) mixtures and bulk blends; (iii) multimicronutrient carriers; and (iv) fortified fertilizers.

A brief historical overview

The use of fertilizers started in the early nineteenth century when saltpetre and guano where shipped from Chile and Peru to the United Kingdom and Western Europe, respectively. The first “artificial fertilizer”, namely SSP, was produced in 1843 in the United Kingdom, to be followed by many SSP factories throughout Europe. Production of potash fertilizers started in 1860 in Germany and of that N fertilizers from ammonia (derived from coal) in about 1890. A significant advance in the production technology of N fertilizers came with the production of synthetic ammonia by the Haber-Bosch process in Germany in 1913. Production and use of urea as a fertilizer started from 1921. Since then, a large variety of solid and liquid fertilizers containing one, two or several plant nutrients have been produced and used. The fertilizer scene is dominated by products containing N, P and K in many chemical and physical forms and their combinations in order to meet the need for their application under different conditions throughout the world.

General aspects

In most countries, the effectiveness and safe use of substances to be registered as fertilizers is ensured by law. Recently, in developed countries, there has been a trend towards regulating some aspects of fertilizer application in respect of pollution.

The nutrient concentration of fertilizers is traditionally expressed in terms of N, P_2O_5 , K_2O , etc. For example, an NPK fertilizer 15–15–15 contains 15 percent each of N, P_2O_5 and K_2O , or 45 percent total nutrients. The percentage composition of a fertilizer refers mostly to the total concentration of a nutrient, but sometimes only to its available portion. For solid fertilizers, the percentage generally refers to the weight basis, e.g. 20 percent N means 20 kg of N in 100 kg of product. For

TABLE 15
Five leading countries in terms of the consumption of mineral fertilizers, 2002–03

Country	Consumption				kg/ha of arable area
	N	P ₂ O ₅	K ₂ O	Total	
	(million tonnes)				
China	25.200	9.854	4.162	39.216	275.0
United States of America	10.878	3.875	4.545	19.298	109.6
India	10.474	4.019	1.602	16.095	99.7
Brazil	1.816	2.807	3.059	7.682	130.2
France	2.279	0.729	0.960	3.968	215.1
World	84.746	33.552	23.273	141.571	100.8

Source: FAOSTAT, 2005.

liquid fertilizers, both weight and volume percentages are used, e.g. 20 percent by weight of N of a solution with the specific weight of 1.3 corresponds to 26 percent by volume (260 g N/litre).

In scientific literature, the nutrients are expressed mostly in elemental form whereas the industry, trade and extension services continue to express P and K in their oxide forms. The fact is that neither N nor P exists in soils, plants or fertilizers in elemental form. In any case, owing to the mismatch between the forms in which plant nutrients are expressed in research, extension and trade literature, care is needed when converting research data into practical values. Where the optimal application rate is reported as 26 kg P/ha in a research document, this translates into 60 kg P₂O₅/ha.

From small beginnings in the nineteenth century, the use of fertilizers has grown dramatically. The total consumption of NPK through fertilizers is now almost 142 million tonnes at an average rate of 100 kg of nutrients (N + P₂O₅ + K₂O) per hectare of arable area (Table 15). Five countries (China, the United States of America, India, Brazil and France) account for 61 percent of the total fertilizer consumption, while more than half of total consumption takes place in China, the United States of America and India.

The nutrient consumption rate in different countries varies from very high to extremely low (Figure 2). Even more than 150 years after the beginning of fertilizer use, there are still large areas of the world where no or very little fertilizer is used.

Fertilizers containing nitrogen

Origin

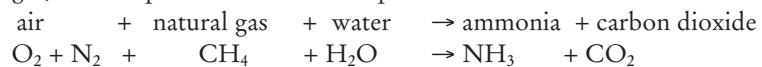
All N in fertilizers originates from the nitrogen gas (N₂) in the atmosphere, which contains 79 percent N by volume. Above every hectare of land at sea level, there are 78 000 tonnes of N₂. This is the N that is converted into ammonia in the fertilizer factories, and this is also the N that is fixed biologically into ammonium by various micro-organisms. Thus, there are abundant supplies of N for the production of nitrogenous fertilizers. Only a small amount of fertilizer N is still obtained from natural deposits such as Chile saltpetre and guano. As the nutrient

N is captured from the air, N fertilizer production is primarily a matter of available energy, which is mainly derived from oil or natural gas reserves.

Production of N fertilizers

The main features of the production of N fertilizers are:

➤ Ammonia: It is the starting point and basic intermediate for the production of N fertilizers. It is synthesized by the Haber-Bosch reaction which combines the very stable molecule of atmospheric N₂ with hydrogen, e.g. from natural gas, under a pressure of 200 atmospheres at 550 °C:



➤ Nitrate fertilizers: In this case, nitric acid (HNO₃) is produced by the oxidation of ammonia and then neutralized with materials such as calcium carbonate (CaCO₃) to produce calcium nitrate Ca(NO₃)₂. Nitrate fertilizers may also be derived from other sources such as Chile saltpetre.

➤ Ammonium nitrate (AN) fertilizers: These are produced by neutralizing nitric acid (derived from the oxidation of ammonia) with ammonia. The solid granulated fertilizer is obtained by spraying the highly concentrated solution in cooling towers.



➤ AN with lime: It is produced: (i) by mixing AN with calcium carbonate to obtain calcium ammonium nitrate (CAN); and (ii) by the reaction of calcium nitrate with ammonia and CO₂.

➤ Urea: It is produced by the reaction of NH₃ and CO₂ at 170 atmospheric pressure and a temperature of 150 °C. Care is needed during drying to ensure that the biuret formed is minimum and within the permissible limits set out in fertilizer-quality standards.

Consumption of N fertilizers

The annual consumption of N through fertilizers is almost 85 million tonnes of N (2002–03 data). Out of this total, more than 50 million tonnes of N is consumed in five countries (China, United States of America, India, France and Brazil). China, India and the United States of America each consume more than 10 million tonnes of N through fertilizers annually. The number of N-containing fertilizers is large. Straight N fertilizers are listed in Table 16 and the major ones are described below. Multinutrient fertilizers containing N are discussed in a later section.

Anhydrous ammonia

Gaseous ammonia can be used directly as a fertilizer. It has a pungent odour and is toxic to plants and humans when concentrated but harmless in dilute form. When liquefied under pressure for transportation, it is referred to as liquid or anhydrous ammonia (containing 82 percent N). It is injected as a gas by special equipment into the soil, where it reacts rapidly with water to form ammonium hydroxide.

TABLE 16
Common straight N fertilizers

Fertilizer	Percent N
Ammonium fertilizers	
Anhydrous ammonia NH ₃	82
Aqua ammonia NH ₄ OH	26
Ammonium sulphate (NH ₄) ₂ SO ₄	21(also 24% S)
Ammonium bicarbonate NH ₄ HCO ₃	17
Ammonium chloride NH ₄ Cl	25
Nitrate fertilizers	
Calcium nitrate Ca(NO ₃) ₂	16 (also 20% Ca)
Sodium nitrate (Chile saltpetre) NaNO ₃	16
Ammonium + nitrate fertilizers	
Ammonium nitrate NH ₄ NO ₃	35
Calcium ammonium nitrate NH ₄ NO ₃ + CaCO ₃	27
Ammonium nitrate sulphate NH ₄ NO ₃ + (NH ₄) ₂ SO ₄	26 (also 15% S)
Amide fertilizers	
Urea CO(NH ₂) ₂	46
Calcium cyanamide CaCN ₂	22
Urea ammonium nitrate fertilizers	
Urea ammonium nitrate solution	28
Slow-release N fertilizers	
Several products, e.g. CDU, S-coated urea, polymer-coated products, oxamide, IBDU	Variable

preparation of ammoniated superphosphate. It is easier to handle than anhydrous ammonia, but because of its low N concentration, it involves higher freight costs per unit of nutrient.

Ammonium sulphate (AS)

AS is the oldest synthetic N fertilizer. It contains about 21 percent N (all as ammonium) and 23–24 percent S (all as sulphate). It is an acid-forming fertilizer and is highly soluble in water. It can be produced through various processes and used directly or as an ingredient of fertilizer mixtures. It is used as part of the basal dressing or as top-dressing to provide both N and S. In S-deficient soils, it works as an N + S fertilizer. AS should not be mixed with PR or urea.

Ammonium nitrate (AN)

AN is produced by neutralizing nitric acid with ammonia. Fertilizer-grade AN has 33–34.5 percent N, of which 50 percent is present as ammonium and 50 percent as nitrate. It is usually in a granular or prilled form and coated with a suitable material to prevent absorption of moisture and caking in storage. It is a valuable N fertilizer, but also a dangerous explosive, hence, its trade and use as fertilizer is forbidden in many countries. It can be rendered harmless by mixing it with calcium carbonate to produce CAN. It is also used to produce liquid fertilizers. AN leaves behind an acidic effect in the soil.

Because of its low price, and in spite of its high application cost, it accounts for a large part of N consumption in some countries, e.g. the United States of America. Special safety precautions are needed during its transportation, handling and application. It is also the major intermediate for the production of other N fertilizers, both straight and complex.

Aqua ammonia

Aqueous ammonia is a solution containing water and ammonia in any proportion, usually qualified by a reference to ammonia vapour pressure. For example, aqua ammonia has a pressure of less than 0.7 kg/cm². Commercial grades commonly contain 20–25 percent N. It is used either for direct application to the soil or in the

Calcium ammonium nitrate (CAN)

CAN is a mixture of AN and finely pulverized limestone or dolomite, granulated together. It contains 21–26 percent N, half in the form of ammonium and the rest in the form of nitrate. Its use does not make the soil acid by virtue of the carbonate in it.

Sodium nitrate

Also known as Chilean nitrate of soda or Chile saltpetre, it was the first mineral N fertilizer to be used. It is obtained by refining the crude nitrate deposits called Caliche found in Chile. It contains about 16 percent N, all as nitrate. Natural saltpetre from Chile is still used as a fertilizer. The product also contains 0.05 percent B, which makes it particularly suitable for fertilizing sugar beets.

Urea

Urea is the most important and widely used N fertilizer in the world today. It is a white, crystalline, non-protein, organic N compound made synthetically from ammonia and CO₂. Urea contains 46 percent N, all in amide (NH₂) form and it is readily water soluble. It is the most concentrated solid N fertilizer that is produced as prills or granules of varying sizes. It is hydrolysed in the soil by the enzyme urease to furnish ammonium and then nitrate ions. During the manufacture of urea, a small amount of biuret (NH₂-CO-NH-CO-NH₂) is also produced. Urea should not contain more than 1.2 percent of the toxic biuret for soil application and not more than 0.3 percent where sprayed on leaves. It is used as a solid N fertilizer for soils, for foliar application, as an ingredient of liquid fertilizers and in NP/NPK complexes. Urea leaves behind an acidic effect in soils. However, this is much smaller than the acidic effect of AS.

Others

N is also provided through a number of liquid fertilizers or fertilizer solutions. One example is the aqueous ammonia discussed above. Another is urea ammonium nitrate solution, which contains 28–33 percent N. Liquid N fertilizers can be high-pressure solutions or low-pressure solutions.

Slow-release fertilizers are of particular importance for special applications and they increase the efficiency of N. These have been developed to better adapt the rate of N release to the N demands of plants, reduce the number of splits required, improve nitrogen-use efficiency and reduce N losses.

There are a large number of slow-release fertilizers and their mixtures, with N-release rates extending from short to long periods. Some examples of slow-release fertilizers are crotonylidene urea (CDU), isobutylidene diurea (IBDU), combinations of formaldehyde and urea, and oxamide (diamide of oxalic acid). Polymer-coated urea has been shown to be an effective N source. However, like the other slow-release products, the cost is high. Different degrees of release can be distinguished by analytical methods with fractions soluble in hot water acting more slowly than those soluble in cold water, and fractions insoluble in hot water

acting extremely slowly. Soil microbes gradually liberate the N in these slow-release fertilizers with the decomposition rate depending largely on temperature. They are expensive in terms of per unit of N and are, therefore, restricted mainly to commercial and special applications.

Fertilizers containing phosphorus

Phosphatic fertilizers contain P, mostly in the form of calcium, ammonium or potassium phosphates. The phosphate in fertilizers is either fully water soluble or partly water soluble and partly citrate soluble, both being considered as plant available. Citrate-soluble P dissolves slowly and is relatively more effective in acid soils. The concentration of P (usually indicated as percent P_2O_5) refers either to the available or the total portion of phosphate.

Origin and reserves

The primary source of phosphate in fertilizers is the mineral apatite, which is primarily tricalcium phosphate $[Ca_3(PO_4)_2]$. It is the major constituent of PR, the basic raw material for the production of phosphatic fertilizers. These phosphate-containing rocks are found in special geological deposits and some phosphate-containing iron ores or other P compounds. PRs consist of various types of apatites. Depending upon the dominance of F, Cl or OH in the apatite crystal structure, it is known as fluorapatite, chlorapatite or hydroxyapatite. Weathering processes over long periods of time resulted in the accumulation of primary apatites or apatite-containing bones, teeth, etc. of animals of earlier geological periods. Many such deposits occur near the earth's surface, from where they are obtained by opencast mining and utilized either directly or after beneficiation for fertilizer production.

Large deposits of PR exist in several parts of the world, for example:

- North Africa (Morocco, Algeria, Tunisia, etc.) in the form of organogenic phosphorite, either as more or less hard rocks or as soft earth phosphate;
- the United States of America, e.g. Florida apatite, which is in the form of moderately hard pebbles and the teeth and bones of sea animals.
- Russian Federation, in the form of hard earth, coarsely crystalline apatite, e.g. magmatic Kola apatite.

It is not always realized that phosphate is a scarce raw material, probably the most critical one. Global reserves (actual and probable) with more than 20 percent P_2O_5 content seem to be in the range of 30–40 000 million tonnes, amounting to about 10 000 million tonnes P_2O_5 . With a future annual consumption of 40–50 million tonnes P_2O_5 , these reserves would last less than 200 years, or may be 100 years assuming an increased rate of consumption. In the past 100 years, phosphate has been discovered at a rate that exceeds the rate of P consumption (Sheldon, 1987). One source of future phosphate production is offshore deposits, which occur on many continents. None of these deposits is currently being mined because ample reserves exist onshore.

Production of P fertilizers

Superphosphate, or rather SSP, was the first mineral fertilizer to be produced in factories in the 1840s in the United Kingdom. There are two principal ways of producing P fertilizers from PRs:

- Chemical solubilization of PR into fully or partially water-soluble form by:
 - Sulphuric acid resulting in SSP:
$$\text{Ca}_3(\text{PO}_4)_2 + \text{H}_2\text{SO}_4 \rightarrow \text{Ca}(\text{H}_2\text{PO}_4)_2 + \text{CaSO}_4$$
tricalcium phosphate + sulphuric acid → [monocalcium phosphate + gypsum] = SSP
 - Phosphoric acid resulting in triple superphosphate (TSP) as follows:
$$\text{Ca}_3(\text{PO}_4)_2 + \text{H}_3\text{PO}_4 \rightarrow \text{Ca}(\text{H}_2\text{PO}_4)_2$$
tricalcium phosphate + phosphoric acid → [monocalcium phosphate] = (TSP)
 - Partial solubilization of PR with lesser amounts of sulphuric acid to produce what are known as partially acidulated phosphate rocks (PAPRs).
- Mechanical fine grinding of reactive PR for direct application as fertilizer.
- For the commercial evaluation of PRs, their total P content is determined using strong mineral acids. Most P fertilizers are evaluated by the “reactive” or “available” portion of their total phosphate content. This is based on chemical solubility, which is supposed to correspond to plant availability. Several solvents are employed for the extraction of the “available” portion of P fertilizers:
 - Water: for SSP, TSP, etc.; extraction of water-soluble phosphate.
 - Neutral ammonium citrate for SSP, PR, etc. is used in some countries to determine quick-acting phosphate. In some cases, the first extract is discarded and the second extract taken for evaluation of PR. High solubility in citrate (> 17 percent) indicates high reactivity.
 - Citric acid (2 percent) for nitrophosphates and Thomas phosphate.
 - Formic acid (2 percent) for PR in some countries. High solubility (> 55 percent) indicates high effectiveness.

Consumption of P fertilizers

The world consumption of phosphate fertilizers is 33.6 million tonnes P₂O₅, accounting for 24 percent of total nutrient usage (Table 15). Almost 63 percent of the global P₂O₅ consumption in 2002–03 occurred in China, India, the United States of America, Brazil and France. China alone accounts for almost 10 million tonnes P₂O₅ consumption through fertilizers. The consumption in terms of arable area ranges from negligible in several countries to 109 kg P₂O₅/ha in Japan, with a world average of 24 kg P₂O₅/ha.

The nutrient composition of major phosphate fertilizers is summarized in Table 17. This is followed by a brief description of common P fertilizers. Ammonium phosphates are discussed under complex fertilizers.

TABLE 17
Some common phosphate fertilizers

Fertilizer	P ₂ O ₅	P (%)
Single superphosphate (SSP): Ca(H ₂ PO ₄) ₂ + CaSO ₄ ·2H ₂ O	16–18	7–8
Enriched superphosphate (ESP) is a special form of SSP	27	12
Triple superphosphate (TSP): Ca(H ₂ PO ₄) ₂ + CaHPO ₄	46–50	20–22
Partly acidulated phosphate rock (PAPR). About 40% water soluble + 30% citric acid soluble P, giving 70 percent "available" portion, contains 20% gypsum	23	10
Basic slag (Thomas phosphate): citric-acid-soluble concentration contains Ca phosphate silicate (75 percent), CaO (5 percent), some Fe, Mn, etc.	10–15	4–7
Phosphate rocks, finely ground (< 0.16 mm): evaluated according to solubility in citrate or formic acid	23–40	10–17

Superphosphates

Single superphosphate (SSP) is the oldest commercially produced synthetic fertilizer and the most common among the group of superphosphates. The prefix "super" probably refers to its superiority over crushed animal bones when it was first produced in the 1840s. SSP is a mixture of monocalcium phosphate [Ca(H₂PO₄)₂] and calcium sulphate or gypsum (CaSO₄·2H₂O). It contains 16 percent water-soluble P₂O₅, 12 percent S in sulphate form and 21 percent Ca. As is clear from its composition, it is known as a straight or single-

nutrient (P) fertilizer only for historical and traditional reasons. Its bulk density is 96.1 kg/m³, critical relative humidity is 93.7 percent at 30 °C and angle of repose is 26°. It is commonly used as part of basal dressing either as such or as part of fertilizer mixtures. Its S component comes from the sulphuric acid used during its manufacture. The Ca component of SSP is particularly valuable for crops such as groundnut during pod formation. SSP should not be mixed with CAN or urea unless the mixture is applied immediately and not stored.

TSP is obtained by treating PR with phosphoric acid. It contains about 46 percent P₂O₅, mainly in water-soluble form. Unlike SSP, it contains very little S.

Basic slag

Basic slag is a by-product of the steel industry. It is considered to be a double silicate and phosphate of lime [(CaO)₅P₂O₅SiO₂]. It contains 10–18 percent P₂O₅ (part of which is citrate soluble), 35 percent CaO, 2–10 percent MgO and 10 percent Fe. Basic slag can be used as a fertilizer-cum-soil conditioner because it contains lime and citric-acid-soluble P. The steel slags are very hard – their use in agriculture is possible only where they are ground to a fine powder.

Thomas phosphate, a type of basic slag, is a by-product of the open-hearth process of making steel from pig iron. It may contain 3–18 percent P₂O₅ depending on the P content of the iron ore. Thomas phosphate (14–18 percent P₂O₅) was a popular phosphate fertilizer in Europe. It is a dark powder and its slow action is well-suited to maintaining soil P levels. The standard specification of Thomas slag is that 70–80 percent of the material should pass through 100 mesh. It has some liming effect. The availability of this fertilizer is decreasing and it is unimportant in much of the world.

Phosphate rock (PR)

PR can also be used directly as a fertilizer. It contains 15–35 percent P_2O_5 . The quality of PR as a fertilizer depends on its age, particle size, degree of substitution in the crystal structure and solubility in acids. PR also contains several micronutrients. Their average contents are 42 mg/kg Cu, 90 mg/kg Mn, 7 mg/kg Mo, 32 mg/kg Ni and 300 mg/kg Zn. Their Cd content varies from 1 to 87 mg/kg of PR. In PRs for direct application, the Cd content should preferably not exceed 90 mg Cd/kg P_2O_5 (27 mg/kg of PR).

Reactive PRs can also be used directly as P fertilizer in acid soils with or without any pre-treatment. Such PRs can be used in acid soils and for long-duration crops. Their suitability depends on the reactivity of the rock, its particle size, soil pH and type of crop. Their suitability for direct application can be estimated by dissolving the PR in certain extracting solutions. The most common solutions are neutral ammonium citrate, 2-percent citric acid and the preferred 2-percent formic acid. The effectiveness of PRs is not only related to the reactive “available” portion but it also depends on the P-mobilization capacity of the soil, which is related to pH, moisture status and biological activity. This means that the final evaluation of PR must be based on field experiments. Several aspects of PR for direct application have been dealt with in detail in publication produced by FAO (2004b).

Partially acidulated phosphate rock (PAPR)

PAPR is obtained by the partial acidulation of PR to convert only a part of its P into water-soluble form, as compared with complete acidulation, where fertilizers such as SSP or TSP are produced. The degree of acidulation is usually referred to in terms of the percentage of acid required for complete acidulation, e.g. to produce SSP. Where only 30 percent of the acid needed to make SSP is used for preparing PAPR, it is referred to as PAPR 30 percent H_2SO_4 . It is an intermediate kind of product between SSP and PR. It can serve as an effective phosphate fertilizer in neutral to alkaline soils that are not highly deficient in P and where long-duration crops are grown. These are widely used in Europe and South America (FAO, 2004a, 2004b).

Others

Dicalcium phosphate ($CaHPO_4$) is a slow-acting product used as a component of multinutrient fertilizers but it is rarely used as a fertilizer by itself in present times. Other P fertilizers are polyphosphates and diluted phosphoric acid (H_3PO_4), which can be used in hydroponics or for preparing liquid fertilizers. The problem of low P-utilization efficiency and the desire to obtain products suitable for fertilizer solutions and fertigation has led to a range of new P fertilizers, such as condensed phosphates (polyphosphates, metaphosphates and ultraphosphates), all with high P concentrations. They are partly water soluble and rapidly hydrolyse in the soil, i.e. convert into the plant available orthophosphate form. Phosphates coupled with sugars (glycido-phosphates) have been found to be useful for fertigation.

There are also liquid fertilizers based on phosphoric acid that may have several other nutrients such as N and micronutrients along with P.

Phosphate fertilizers can also be derived from the processing of municipal wastewaters, namely iron and aluminium phosphates. Where practically free of toxic impurities, these are valuable although slow acting and are likely to gain greater importance in the future.

Fertilizers containing potassium

Potash fertilizers are predominantly water-soluble salts. For historical reasons, their K concentration is generally still expressed as percent K₂O, particularly by the industry, trade and extension. As such, the nutrient K does not exist as K₂O in soils, plants or in fertilizers. It is present as the potassium ion K⁺ in soils or plants and as a chemical compound (KCl, K₂SO₄) in fertilizers.

Origin and reserves

Large deposits of crude K salts were first found in Germany in the mid-1850s. In recent times, deposits in several countries, especially in Canada, have been mined and utilized for the production of potash fertilizers. Canada and the countries of the former Soviet Union have 90 percent of the known potash reserves (IFA, 1986). These deposits were formed millions of years ago during the process of drying up of seawater in former ocean basins. Layers of common salt (NaCl) were overlain by smaller layers of K minerals, which hardened to rock under pressure. Crude K salts are thus natural seawater minerals, which are now mined from great depths. World K reserves are large and more are expected to be discovered.

Production and consumption

The first potash fertilizers were ground crude K salts containing 13 percent K₂O. These are still used to some extent for fertilization of grassland in order to supply K and Na. They are also accepted in biofarming as a natural fertilizer. The main K fertilizers used at present are purified salts.

The production of potassium chloride (KCl) or MOP involves grinding of the salt rocks, which consist of minerals such as kainite (19 percent K₂O) and carnallite (17 percent K₂O). The unwanted components such as Na, Mg and Cl are then separated, which involves heating (dissolution of salts) followed by crystallization of KCl upon cooling. In the newer flotation process, KCl crystals are coupled with organic agents, floated to the surface and removed. Electrostatic methods separate solid crystals of KCl from other compounds.

Potassium sulphate is produced by the chemical reactions of different crude salts as also by the reaction of KCl with sulphuric acid. Besides the salt deposits, there are K-containing industrial waste products, e.g. dust from cement production, that can serve as a K fertilizer.

World consumption of K through fertilizers was 23.3 million tonnes K₂O in 2002–03. This amounted to about 16 percent of the total nutrient consumption through fertilizers. Almost 62 percent of total potash consumption takes place in

five countries (the United States of America, China, Brazil, India and France) with the United States of America, China and Brazil accounting for 50 percent of the total potash consumption. Unlike most countries, potash consumption exceeds phosphate consumption in large-consuming countries such as the United States of America, Brazil and France while it is well below phosphate consumption in India and China. At the global level, potash consumption ranges from negligible in many areas to 107 kg K₂O/ha of arable area in the Republic of Korea, with a world average of 16.6 kg K₂O/ha.

Potassium chloride (MOP)

Potassium chloride (KCl), also called muriate of potash (MOP), is the most common K fertilizer. It is readily soluble in water and is an effective and cheap source of K for most agricultural crops. Grades of MOP vary from 40 to 60 percent K₂O. Fertilizer containing 60 percent K₂O is almost pure KCl containing about 48 percent Cl. MOP comes as powders or crystals of varying colours and hues from white to pink but these differences have no agronomic significance. Its critical relative humidity is 84 percent at 30 °C and it has a higher salt index than potassium sulphate. It is used either directly as a fertilizer or as an ingredient of common NPK complexes.

Potassium sulphate (SOP)

SOP is actually a two-nutrient fertilizer containing 50 percent K₂O and 18 percent S, both in readily plant available form. It is costlier than MOP but is particularly suitable for crops that are sensitive to chloride in place of KCl. It has a very low salt index (46.1) as compared with 116.3 in case of MOP on material basis. It also stores well under damp conditions. SOP should not be mixed with CAN or urea.

Others

Other important sources of potash such as potassium magnesium sulphate and potassium nitrate are discussed under multinutrient fertilizers in a later section. As there may be some salinity damage with high K applications, particularly as MOP (especially in gardening), slow-acting K fertilizers such as less soluble double salts, fritted K containing glass and soluble-coated K salts have been developed. Special rock powder, e.g. from potassium feldspar, is an extremely slow-acting K fertilizer, even after fine grinding.

Fertilizers containing sulphur

Most S-containing fertilizers are in fact sulphate salts of compounds that also contain other major nutrients or micronutrients. S-containing fertilizers such as AS, SSP and SOP have been discussed above under the respective sections on fertilizers containing N, P or K. Multinutrient fertilizers including NP/NPK complexes containing S as also liquid fertilizers (e.g. ammonium thiosulphates) are discussed in a later section. The only truly single-nutrient S fertilizers are the elemental S products.

Some sources of S and their approximate S content are:

- ammonium sulphate $(\text{NH}_4)_2\text{SO}_4$: contains 24 percent S;
- ammonium sulphate nitrate $(\text{NH}_4)_2\text{SO}_4 \cdot \text{NH}_4\text{NO}_3$: contains 12 percent S;
- SSP: contains 12 percent S;
- ammonium phosphate sulphate: contains 15 percent S;
- potassium sulphate (K_2SO_4) : contains 18 percent S;
- potassium magnesium sulphate $(\text{K}_2\text{SO}_4 \cdot 2\text{MgSO}_4)$: contains 22 percent S;
- magnesium sulphate monohydrate $(\text{MgSO}_4 \cdot \text{H}_2\text{O})$: contains 22 percent S;
- magnesium sulphate heptahydrate $(\text{MgSO}_4 \cdot 7\text{H}_2\text{O})$: contains 13 percent S;
- gypsum/phosphogypsum $(\text{CaSO}_4 \cdot 2\text{H}_2\text{O})$: contains 13–17 percent S;
- elemental S products: contain 85–100 percent S;
- sulphur bentonite: contains 90 percent S;
- pyrites (FeS_2): contains 18–22 percent S;
- sulphate salt of micronutrients: contain variable amounts of S.

Formulations containing S in elemental form are increasingly finding use as S fertilizers (Messick, de Brey and Fan, 2002). Elemental S products are the most concentrated source of S. The elemental S in them has first to be oxidized to sulphate in the soil by bacteria (*Thiobacillus thiooxidans*) before it can be absorbed by plant roots. The rate of S oxidation depends on the particle size of the fertilizer, temperature, moisture, degree of contact with the soil, and level of aeration. To facilitate oxidation from S to SO_4^{2-} , elemental S sources are usually surface applied a few weeks ahead of planting.

Fertilizers containing calcium

Raw materials for Ca fertilizers are abundant as whole mountains consist of calcium carbonate (CaCO_3) and there is no shortage of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) either as a mineral or as a by-product (phosphogypsum) of the wet-process phosphoric acid production. Common Ca fertilizers are:

- calcium oxide (CaO): contains 50–68 percent Ca ($\text{Ca} \times 1.4 = \text{CaO}$);
- slaked lime $[\text{Ca}(\text{OH})_2]$: contains 43–50 percent Ca;
- agricultural limestone (CaCO_3): contains 30–38 percent Ca;
- dolomite ($\text{CaCO}_3 \cdot \text{MgCO}_3$): contains 24–32 percent Ca;
- CAN: contains 7–14 percent Ca;
- calcium nitrate $[\text{Ca}(\text{NO}_3)_2]$: contains 20 percent Ca;
- calcium chloride $(\text{CaCl}_2 \cdot 6\text{H}_2\text{O})$: 15–18 percent Ca;
- SSP: contains 18–21 percent Ca;
- gypsum $(\text{CaSO}_4 \cdot 2\text{H}_2\text{O})$: contains 23 percent Ca;
- calcium chelates: variable.

Calcium nitrate contains about 15 percent N and 28 percent CaO. It is a good source of nitrate N and water-soluble Ca and is particularly used for fertilizing horticultural crops and for fertigation. Calcium nitrate is suitable only where N application may also be required. Water-soluble Ca fertilizers such as calcium chloride or calcium nitrate may be applied as foliar sprays. A component of several

commercial leaf sprays, calcium chloride solutions with 10 percent Ca are used for spraying fruits such as apples.

Gypsum, with its moderate water solubility, is a very useful Ca fertilizer for soil application, but few soils need it to increase Ca supply. The main role of mineral gypsum is on alkali (sodic) soils for the removal of toxic amounts of Na and to supply S in deficient situations. The same is true of phosphogypsum, where it is not contaminated with heavy metals such as Cd.

Fertilizers containing magnesium

Natural reserves of Mg are very large, both in salt deposits ($MgCl_2$, $MgCO_3$, etc.) and in mountains consisting of dolomite limestone ($CaCO_3.MgCO_3$). There are several commercially available materials of acceptable quality that can be used to provide Mg to soils and plants. There are two major groups of Mg fertilizers, namely, water soluble and water insoluble. Among the soluble fertilizers are magnesium sulphates, with varying degree of hydration, and the magnesium chelates. The sulphates can be used both for soil and foliar application whereas the chelates, such as magnesium ethylenediamine tetraacetic acid (Mg-EDTA), are used mainly for foliar spray. Some sources of Mg are:

- magnesium oxide (MgO): contains 42 percent Mg ($Mg \times 1.66 = MgO$);
- magnesite ($MgCO_3$): contains 24–27 percent Mg;
- dolomitic limestone ($MgSO_4.CaSO_4$): contains 3–12 percent Mg;
- magnesium sulphate anhydrous ($MgSO_4$): contains 20 percent Mg;
- magnesium sulphate monohydrate ($MgSO_4.H_2O$): contains 16 percent Mg;
- magnesium sulphate heptahydrate ($MgSO_4.7H_2O$): contains 10 percent Mg;
- magnesium chloride ($MgCl_2.6H_2O$): contains 12 percent Mg;
- potassium magnesium sulphate ($K_2SO_4.2MgSO_4$): contains 11 percent Mg.

Magnesium sulphate is the most common Mg fertilizer. In anhydrous form, it contains 20 percent Mg. As a hydrated form, $MgSO_4.7H_2O$ (Epsom salt), it contains 10 percent Mg. It is readily soluble in water, has a bulk density of 1 g/cm^3 and an angle of repose of 33° . It can be used for soil application and for foliar application. Kieserite is the monohydrate form of magnesium sulphate ($MgSO_4.H_2O$). It contains 16 percent Mg and is sparingly soluble in cold water but readily soluble in hot water. Its bulk density is 1.4 g/cm^3 and its angle of repose is 34° . It is used as a fertilizer for soil or foliar application to provide Mg as well as S.

Among the insoluble or partially water-soluble sources are magnesium oxide, magnesium carbonate and magnesium silicates. The insoluble or partially soluble materials are used more often as liming materials. However, in acid soils, they can also be used as Mg fertilizers. Magnesium carbonate, the major component of the mineral magnesite, is also used as a raw material for the production of magnesium sulphate.

Fertilizers containing nitrogen and phosphorus (NP)

These are not only the starting materials for the production of NPK fertilizers but they are also used for the simultaneous supply of two major nutrients (N and P)

required in many cropping systems. They are produced by different processes and their nutrient concentration is indicated in percent N + P₂O₅.

The main solid types of NP fertilizers are mono-ammonium phosphate (MAP), di-ammonium phosphate (DAP), nitrophosphates, urea ammonium phosphates and ammonium phosphate sulphates. NP solutions consist of ammonium phosphate and polyphosphates with a specific gravity of about 1.4 and nutrient concentrations about 10 percent N + 34 percent P₂O₅. Special-purpose NP types are ultrahigh concentration fertilizers that are not phosphates but phosphonitrides or metaphosphate with a composition of 43 percent N + 74 percent P₂O₅ as an example (sum of nutrients > 100 percent if based on P₂O₅), but actually 43 percent N + 33 percent P.

Mono-ammonium phosphate (MAP)

MAP (NH₄H₂PO₄) is produced by reacting phosphoric acid with ammonia. It contains 11 percent N and 55 percent P₂O₅. It can be used directly as an NP fertilizer for soil application or as a constituent of bulk blends. It can also be fortified with S to make it more effective on S-deficient soils.

Di-ammonium phosphate (DAP)

DAP [(NH₄)₂HPO₄] is an important finished fertilizer as well as an intermediate in the production of complex fertilizers and bulk blends. It is produced by treating ammonia with phosphoric acid. It typically contains 18 percent N + 46 percent P₂O. About 90 percent of the total P is water soluble and the rest is citrate soluble. In some countries, efforts are underway to fortify DAP with the needed micronutrients.

Ammonium nitrate phosphate (ANP)

ANP is produced by reacting PR with nitric acid. Several grades are produced and a typical grade contains 20 percent N and 20 percent P₂O₅. Also known as nitric phosphates or nitrophosphates, all of them contain 50 percent of the total N in nitrate form and 50 percent as ammonium. Part of the total phosphate (30–85 percent) is water soluble, the rest being citrate soluble. Products with less water-soluble P are more efficient in acid soils or soils that are at least of medium P fertility, particularly for long-duration crops. In neutral to alkaline soils, particularly for short-duration crops, 60 percent or higher levels of water-soluble P₂O₅ content are generally preferred.

Ammonium phosphate sulphate (APS)

These are in reality three-nutrient fertilizers containing N, P and S, all in water-soluble, plant available forms. APS can be seen as a complex of AS and ammonium phosphate. Both the common grades (16–20–0) and 20–20–0 also contain 15 percent S, which comes from the AS portion.

Urea ammonium phosphates (UAPs)

UAPs are produced by reacting ammonia with phosphoric acid to which urea is also added in order to increase the N content in the product. The most common example of this type of NP complex is 28–28–0 (the first UAP to be commercially produced in the world). As the name suggests, it contains part (68 percent) of its N in the amide (urea) form and the rest (32 percent) in ammonium form. All its nutrients are readily soluble in water and in available form, amide N being available after conversion into ammonium.

Fertilizers containing nitrogen and potassium (NK)

Of the fertilizers containing N and K, potassium nitrate is perhaps the most important. It typically contains 13 percent N and 44 percent K₂O (37 percent K). It is a good source of K and N for crops that are sensitive to chloride. It finds greatest use for intensively grown crops, such as tomatoes, potatoes, tobacco, leafy vegetables and fruits, and in greenhouses. It has a moderate salt index (between that of MOP and SOP) and is also less hygroscopic. It is useful for normal application and also for fertigation.

Fertilizers containing nitrogen and sulphur (NS)

Fertilizers containing N and S have already been mentioned under nitrogenous fertilizers. Common types are AS, ammonium sulphate nitrate and combinations of urea with ammonium sulphate. S-coated urea is a slow-release fertilizer. Fertilizers such as AS are ideal for top-dressing a growing crop where S deficiency has been detected and an N application is also required. They combine two important nutrients for crops with high S demand.

Ammonium thiosulphate is a liquid NS fertilizer containing 12 percent N and 26 percent S (thio refers to sulphur). Fifty percent of its S is in the sulphate form and the rest is in elemental form. It can be used directly or mixed with neutral to slightly acid P-containing solutions or aqueous ammonia or N solutions to prepare a variety of NPK + S and NPKS + micronutrient formulations. It can also be applied through irrigation, particularly through drip and sprinkler irrigation systems.

Fertilizers containing nitrogen, phosphorus and potassium (NPK)

Theoretically, with 6 major nutrients, there are 20 possible combinations of three nutrient fertilizers. The most prominent ones of these are NPK fertilizers. These can be complex/compound fertilizers, mixtures or bulk blends. In fact, even some so-called single-nutrient or straight fertilizers such as superphosphate can belong to this group as they contain P, Ca and S.

There are a large number of standard-type NPK fertilizers with different nutrient ratios. Their nutrient concentrations are indicated as percentage of N + P₂O₅ + K₂O, the individual nutrient concentrations ranging from about 5 percent to more than 20 percent. While a different fertilizer for every crop and field may

appeal to sophisticated farmers, the majority of growers use a limited number of standard types. Most NPK types are produced by the acid decomposition of PR with incorporation of ammonia, thus producing an NP fertilizer to which a K salt, usually MOP or SOP, is added. These can be solid or liquid fertilizers.

Solid NPK fertilizers

More than 50 types are available on the market, with the N and P components being present in one or several forms. Thus, even in NPK fertilizers with the same grade or nutrient ratio, a given nutrient can be present in several chemical forms (Table 18). In most NPK complexes, the K component is often derived from MOP, but some types contain K through SOP, which makes them suitable for many chloride sensitive plants and horticultural crops. Some NPK fertilizers contain Mg as an additional component. This is often through magnesium sulphate, which makes them suitable for crops with high Mg requirements. This actually results

TABLE 18
Forms of nitrogen and phosphate in various NP/NPK fertilizers

Fertilizer (grade)	Percent N as			Percent P ₂ O ₅ as	
	NH ₄	NO ₃	NH ₂	WS ¹	CS ²
Di-ammonium phosphate (18-46-0)	18.0	0	0	41.0	46.0
Ammonium phosphate sulphate (16-20-0)	16.0	0	0	19.5	20.0
Ammonium phosphate sulphate (20-20-0)	20.0	0	0	17.0	20.0
Ammonium nitrate phosphate (20-20-0)	10.0	10.0	0	12.0	20.0
Ammonium nitrate phosphate (23-23-0)	11.5	11.5	0	18.5	23.0
Ammonium nitrate phosphate (23-23-0)	13.0	10.0	0	20.5	23.0
Urea ammonium phosphate (28-28-0)	9.0	0	19.0	25.2	28.0
Urea ammonium phosphate (24-24-0)	7.5	0	16.5	20.4	24.0
Mono-ammonium phosphate (11-52-0)	11.0	0	0	44.2	52.0
Ammonium polyphosphate (10-34-0) (liquid)	10.0	0	0	22.1	34.0
Nitrophosphate with K (15-15-15)	7.5	7.5	0	4.0	15.0
NPK complex (15-15-15)	12.0	0	3.0	12.0	15.0
NPK complex (17-17-17)	5.0	0	12.0	14.5	17.0
NPK complex (17-17-17)	8.5	8.5	0	13.6	17.0
NPK complex 18-18-18 (100 % ws ¹)	8.2	9.8	0	18.0	18.0
NPK complex (19-19-19)	5.6	0	13.4	16.2	19.0
NPK complex 19-19-19 (100 % ws ¹)	4.5	4.0	10.5	19.0	19.0
NPK complex 20-20-20 (100 % ws ¹)	3.0	4.9	12.1	20.0	20.0
NPK complex (10-26-26)	7.0	0	3.0	22.1	26.0
NPK complex (12-32-16)	9.0	0	3.0	27.2	32.0
NPK complex (22-22-11)	7.0	0	15.0	18.7	22.0
NPK complex (14-35-14)	14.0	0	0	29.0	35.0
NPK complex (14-28-14)	8.0	0	6.0	23.8	28.0
NPK complex (20-10-10)	3.9	0	17.1	8.5	10.0
NPK complex 13-5-26 (100 % ws ¹)	6.0	7.0	0	5.0	5.0
NPK complex 6-12-36 (100 % ws ¹)	1.5	4.5	0	12.0	12.0
Calcium nitrate (15.5 % N, 18.8 % Ca)	1.1	14.4	0	0	0
Mono-ammonium phosphate (12-61-0) (100 % ws ¹)	12.0	0	0	61.0	61.0
Monopotassium phosphate (0-52-34) (100 % ws ¹)	0	0	0	52.0	52.0
Potassium nitrate (13-0-45)	0	13.0	0	0	0

¹Water soluble; ²Citrate soluble.

Source: Tandon, 2004.

into a fertilizer containing four major nutrients. NPK fertilizers are granulated for uniform distribution. Their colour is often greyish but, in order to be better recognized by farmers, some fertilizers are specially coloured in some countries, e.g. red may indicate a composition of 13–13–21, yellow of 15–15–15, and blue of 12–12–20 with K as sulphate.

Liquid NPK fertilizers

For more accurate and convenient application of fertilizers on large farms, liquid fertilizers offer certain advantages. Farmers do not need to carry fertilizer bags, they simply rely on pumping. Spraying machines used for crop protection can be used but suspensions require special nozzles. There are two different types of liquid fertilizers:

- Fertilizer solutions: These are clear liquid fertilizers of low to medium nutrient content. In most of these, the sum of nutrients adds up to 30 percent and they have a specific gravity range of 1.2–1.3. Their common components are urea, ammonium, nitrate, ammonium phosphate and a K salt.
- Suspensions: These are saturated solutions with fine crystals in a stabilized condition in which the sum of nutrients can be up to 50 percent. Their specific gravity is about 1.5. Their components are urea, ammonium, nitrate, polyphosphates and other phosphates, and a K salt.

For both types, the nutrient ratios vary in a wide range from 5:8:15 up to 25:6:20 (N:P₂O₅:K₂O).

The optimal nutrient ratio in NPK fertilizers

On the question of optimal nutrient ratios in NPK fertilizers, theoretical considerations and the actual trend are not in agreement. Strictly speaking, nutrient ratios should be fine tuned to every cropped field. However, in practice, this is neither possible nor necessary. Farmers want to handle as few fertilizers as possible.

A practical approach to the optimal nutrient ratio is derived from nutrient removal data. Decades ago in Western Europe, average rotations removed nutrient from the fields in an N:P₂O₅:K₂O ratio of 1:0.5:1.2. This figure was corrected for the different utilization ratios, which resulted in a final ratio of 1:1:1.6. This was the basis for the common NPK fertilizer of 13:13:21. In recent decades, the ratio has become increasingly dominated by N with a tendency towards 1:0.5:0.5. This is partly explained by greater the buildup of P and K in the soils over the years and the consumers' emphasis on N supply.

In India, which is the world's third-largest user of fertilizers, on a macrolevel, balanced nutrient application is represented by the ratio 1:0.5:0.25. This historical ratio has represented the trend of importance given to fertilizer nutrients and the extent to which these are qualitatively deficient in Indian soils. This ratio bears no relationship to the ratio in which plant nutrients are absorbed by crops or the ratio in which these are removed with the harvest. The overall ratio in which nutrients are removed by crops in India is 1:0.45:1.75. Although a large number of NPK complexes with a wide range of nutrient ratios are produced and used in India,

there is no such thing as an ideal ratio that can be applied over large areas. Even within a given region, the optimal nutrient ratio can never be the same for diverse crops (grains, fodders, fruits, sugar cane, tea, etc.).

At present, the nutrient ratio of global fertilizer consumption is about 1:0.4:0.3. Differences in ratios among countries are as large as between regions within the same country. The search for a single optimal ratio or a few ratios is thus futile for large countries with diverse soils and cropping systems. With increasing emphasis on precision farming and site-specific nutrient management (SSNM), it is best that the optimal ratio be determined by the soil, the crop and the growth conditions.

Fertilizers containing other combinations of major nutrients

Fertilizers containing N and Mg are suitable for supplying these two nutrients in the growing season. They contain AS or AN combined with magnesium sulphate or magnesium carbonate (as dolomite). Micronutrients may be added, such as 0.2 percent Cu for grassland. Potassium magnesium sulphate is a unique three-nutrient fertilizer without N. It typically contains 11 percent Mg, 22 percent K₂O and 22 percent S. Potassium magnesium sulphate is used where the application of S and K is also required. It contains less than 1.5 percent Cl. It has a neutral effect on soil reaction but should not be mixed with urea or CAN.

Micronutrient fertilizers

The importance of fertilizers containing micronutrients has been increasing over the years for several reasons. Decades ago, at medium yield levels, fertilization with micronutrients was restricted to the recovery of acute visible deficiencies that occurred in some areas of sandy, metal-fixing, overlimed or just poor soils. However, on most soils, the natural soil supply of micronutrients was adequate, so that micronutrients were not a large component of fertilization programmes.

With intensive cropping and high yields, the situation has changed considerably (Chapters 4, 6 and 7). For several micronutrients, there are now increasing reports of insufficient soil supplies to meet increased crop requirements. This is affecting both crop yields and produce quality. Increasingly, micronutrients have become yield-limiting factors and are partly responsible for a decreasing efficiency of NPK fertilizers. Therefore, standard NPK-based fertilization must often be supplemented by the deficient micronutrients.

Of the six practically relevant micronutrients, deficiencies of Fe, Mn and Zn tend to occur more on neutral to alkaline soils and under arid and semi-arid conditions. A deficiency of B and Cu is more likely to occur on acid soils in humid climates although large-scale B deficiencies have been reported from many neutral to alkaline soils in east India. Common micronutrient fertilizers are briefly described here. Chapters 7 and 8 provide their application guidelines.

Boron fertilizers

Historically, Chile saltpetre was the first B fertilizer used. Its excellent effect on crops such as sugar beets was not only due to the N but also to the B contributed

by the small amount of borax present in it. This B contribution was not recognized during the first 70 years of its use.

Common B fertilizers are sodium tetraborate or borax ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$) (10.5 percent B), boric acid (H_3BO_3) (17 percent B), Solubor $\text{Na}_2\text{B}_4\text{O}_7 \cdot 5\text{H}_2\text{O}$ + $\text{Na}_2\text{B}_{10}\text{O}_{16} \cdot 10\text{H}_2\text{O}$ (19 percent B), and boron frits. Borax, or sodium tetraborate, is the standard B fertilizer. It is a white gritty salt suitable both for soil and foliar application. Boric acid is more soluble but relatively toxic to plants where applied as a foliar spray. The best fertilizers for spraying on leaves are polyborates. For soil application, borax involves the risk of B toxicity to sensitive plants. However, there are slow-acting B fertilizers, such as colemanite or fritted boron silicates (fine glass powder containing B), that are safe. However, they lack a rapid initial supply.

On B-deficient soils, about 1–2 kg B/ha may be needed for high yields. As the actual fertilizer amounts applied are small and difficult to distribute evenly, B is usually supplied together with special combined fertilizers (N or P or NPK with B).

Chlorine fertilizers

The nutrient Cl is often present in the soil in adequate amounts or is incidentally added through chloride-containing fertilizers and in some cases through irrigation water or seaspray in coastal areas. Chloride deficiency is not common. It has been encountered in palms cultivated away from coastal areas. Common fertilizers containing Cl are KCl (47 percent Cl), NP/NPK complexes in which KCl is an input, sodium chloride (60 percent Cl) and ammonium chloride (66 percent Cl).

Copper fertilizers

Cu fertilizers were first used for the treatment of Cu deficiency in boggy soils to correct the “heath-bog disease” of oats or for the “lick disease” of cattle raised on Cu-deficient grassland because humic substances tend to fix Cu in unavailable forms. Some common Cu fertilizers are: copper sulphate $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ (24 percent Cu), $\text{CuSO}_4 \cdot \text{H}_2\text{O}$ (35 percent Cu); and copper chelate $\text{Na}_2\text{Cu-EDTA}$ (12–13 percent Cu).

Copper sulphate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$) is the oldest and best-known fertilizer. It is a blue salt containing 24 percent Cu or 35–36 percent Cu with less water in its structure. It comes in particle sizes varying from fine powder to granular and is used either in solid form for soil application or as a dilute solution for foliar spraying, which is more effective than soil application. For foliar spraying, copper oxychloride and copper chelate are preferable to the sulphate salts. Cu fertilizers based on metallic oxide and silicate forms can also be used to treat Cu-deficient soils. These substances must first be solubilized in the soils, i.e. converted into Cu^{2+} ions. These are more suitable for long-term Cu supply, in contrast to copper sulphate, which is more suitable for immediate effect. Some fertilizers for grasslands contain both Cu and Zn and even Co.

Iron fertilizers

The majority of Fe fertilizers are water-soluble substances, being either salts or organic complexes (chelates). Common Fe fertilizers are ferrous sulphate $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ (19 percent Fe) and ferrous ammonium sulphate $(\text{NH}_4)_2\text{SO}_4 \cdot \text{FeSO}_4 \cdot 6\text{H}_2\text{O}$ (16 percent Fe), which is in fact a three-nutrient fertilizer containing N, S and Fe. Other important Fe fertilizers are iron chelates, iron polyflavonoides (10 percent Fe) and iron frits, which have variable Fe content.

Ferrous sulphate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$) is a common fertilizer but in many countries there is greater acceptability of iron chelates for foliar spraying. Iron chelates are the principal Fe-containing fertilizers for soil and foliar application in many developed countries and becoming popular in other countries as well. Common Fe chelates in use are:

- Fe-EDTA = ethylenediamine tetraacetic acid with 5–12 percent Fe (Fe^{2+});
- Fe-EDDHA = ethylenediamine di(o-hydroxyphenyl) acetic acid with 6 percent Fe (Fe^{3+}).

Fe uptake by the leaves is greater from chelates than from salts. In the soil, the chelates protect the Fe against rapid fixation. Moreover, chelates have a less damaging effect on leaves. For application on Fe-fixing soils, which are generally neutral to alkaline, the stability of the chelate in the soil is important. In this respect, Fe-EDDHA is more stable and effective than Fe-EDTA.

Manganese fertilizer

Important Mn fertilizers are manganese sulphate $\text{MnSO}_4 \cdot \text{H}_2\text{O}$ (30.5 percent Mn), manganese oxide MnO (41–68 percent Mn), manganese frits (10–35 percent Mn), and Mn chelates (5–12 percent Mn). Manganese sulphate is a pink salt that is water soluble and can be used both for soil treatment and for foliar application. It is also a constituent of Mn-containing multinutrient fertilizers. As in the case of Fe, Mn chelates are more effective than salts. Other Mn fertilizers for soil application are various manganese oxides, manganese carbonate and manganese phosphate. These can be used mainly for soil application. Manganese oxides are mobilized through bacterial reduction under acid conditions, thus converting unavailable MnO_2 into available Mn^{2+} ions.

Mn fertilization is problematical as Mn deficiency is usually not caused by soil impoverishment but by Mn fixation, which decreases the available Mn. Mn fertilizers are not very effective in Mn-deficient soils and whatever effect they have may be small and not long lasting, because soluble Mn is fixed rapidly. Soil acidifying N-fertilizers can even be more effective than Mn fertilizers.

Molybdenum fertilizers

The standard Mo fertilizer is sodium molybdate ($\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$) with 40 percent Mo, but ammonium molybdate $[(\text{NH}_4)_6 \text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}]$ (54 percent Mo) is also suitable. Both products are water soluble and quick acting. These are used for soil and for foliar application. Other potential sources of Mo are molybdenum oxide MoO_3 (66 percent Mo) and molybdenum frits.

Zinc fertilizers

Common Zn fertilizers are zinc sulphates, Zn-EDTA chelate (12 percent Zn), zinc oxide ZnO (55 percent Zn), zinc frits (variable Zn content) and natural Zn chelates. Zinc sulphate is the most common fertilizer and it is available either as ZnSO₄.7H₂O (21 percent Zn) or ZnSO₄.H₂O (33 percent Zn). It can be used for soil or foliar application and like all sulphate salts also provides S. It is less suitable for foliar application because of its acidic action, for which zinc sulphate with some lime is preferable, or Zn chelates like Zn-EDTA can be used. Zinc oxide (ZnO) can be used for soil application, for pre-plant dipping of roots of rice seedlings in its slurry and also soaking of potato-cut seed tubers before planting.

Zn mobilization in soil is aided by acid-forming N fertilizers such as AS or other substances, e.g. pyrite (FeS₂), which produce localized areas of sulphuric acid in soil thus solubilizing Zn.

Combinations of micronutrients

On soils deficient in several micronutrients, multiple micronutrient fertilizers are required. However, this principle is more appropriate for soils under horticultural crops than for soils where only one or two nutrients may be limiting as in case of field crops. In horticulture, particularly for fruit trees, slow-release micronutrient fertilizers are required that can provide a continuous supply of all micronutrients without damage caused by excess supply at a given time. Such fertilizers, with several or all micronutrients, are generally partly water soluble but have mainly slow-acting components. Where applied at planting time, they are effective during the whole growth period.

A large number of multimicronutrient formulations have been developed in several countries. These are meant for soil application or for foliar spray. As is the case with all such formulations, there is always a chance that some nutrients are underapplied and some are overapplied. These umbrella-type formulations are sometimes also seen as prophylactic applications. There is a persistent disagreement between the research data on micronutrient deficiencies and the composition of commercial formulations of multimicronutrient fertilizers marketed in a given area.

Fertilizers containing major nutrients and micronutrients

Some fertilizers are more or less “complete” fertilizers in which many if not all nutrients are present. However, their use has remained limited as, under most cropping systems, not all nutrients need to be supplemented. Nevertheless, some complete fertilizers have a special place in agriculture, particularly in gardening. For example, fertilizers containing N, P, K, Mg and S are enriched with micronutrients Mn, Cu and B, resulting in an eight-nutrient fertilizer that has widespread applicability. Similarly, others are based on slow-acting N and permit a complete nutrient supply to potted plants when applied at planting time, or serve as a lawn fertilizer for the whole vegetative period with no problems of toxicity caused by excess supply early in the season.

Aqueous solutions with all or most nutrients have been developed for foliar application and also for crops where the cause of poor growth is unknown. The problem with such products is that rarely do all nutrients need to be applied, and the really deficient nutrients might be added in insufficient amounts while the not so deficient nutrients may be delivered in excess.

Another view, important for intensive high-value cropping, is based on the consideration that, during vegetative growth, a number of nutrients must be added in order to prevent the minimum factors from limiting growth and yields. As, without precise diagnosis, farmers do not know what is limiting, they tend to use combinations of nutrients that are or might be in short supply. There are numerous products containing various combinations of major nutrients and micronutrients on the market. Whether and to what extent each of their components makes a positive contribution to plant nutrition and economic yield gain is extremely difficult to confirm.

Multinutrient (macro plus micro) applications may take care of existing nutrient deficiencies where applied in time at required intervals. Therefore, they have their place in nutrient management in the absence of accurate information about the nutrient status of a given soil and crop. Money spent on nutrients that are not really needed is the price for a lack of precise information and may be as an insurance against unforeseen limiting factors. However, these are no substitutes for a good nutrient supply from the soil, which must be planned before planting the crop with the help of a good soil test.

Fortified and speciality fertilizers

Apart from the conventional fertilizers described above, there are a number of fortified fertilizers and speciality fertilizers that are targeted at specific situations. Many countries have a fertilizer legislation in which the definition and list of approved fertilizers is provided. Strictly speaking, only such fertilizers can be produced, labelled and marketed as fertilizers. In reality, the number of products in a given market is much larger than the number of officially approved fertilizers. Many products containing plant nutrients and non-essential beneficial elements and also other constituents are often sold as soil improvers, plant growth promoters, or yield enhancers in order to bypass the conditions laid down in the fertilizer legislation. However, several of these have a role to play in meeting the nutrient needs of modern high-technology farming.

Fortified fertilizers

Fortified fertilizers are generally common fertilizers to which one or more specific nutrients have been added in order to increase their nutrient content and make them more versatile. These are also useful for applying the very small quantities of some micronutrients. Some examples of fortified fertilizers are:

- zincated urea, containing 2 percent Zn;
- boronated SSP, containing 0.18 percent B;
- DAP and NPK complexes fortified with 0.5 percent Zn or 0.3 percent B;

- SSP fortified with elemental S, containing 20–50 percent S or with 0.05 percent Mo;
- TSP coated with elemental S to contain 10–20 percent S;
- MAP fortified to contain 10–12 percent elemental S.

Speciality fertilizers

Speciality fertilizers are mainly produced to cater to special crop-production or nutrient-delivery systems. These systems include: intensive indoor farming, greenhouse farming, intensive cultivation of speciality crops, and fertigation. Most of the speciality fertilizers are either fully water-soluble formulations, slow-release materials or material containing organic compounds (humates and amino acids). They may contain one, two or several nutrients (macro and micro). Fertilizers for drip irrigation systems have to be fully water soluble so that they do not leave any residue that will clog the nozzles. In several cases, these are purified versions of common fertilizers that give 100-percent water solubility. Some examples of such fertilizers are:

- monopotassium phosphate containing 52 percent P_2O_5 and 34 percent K_2O ;
- NPK complexes of various grades that are 100 percent water soluble (Table 18);
- seaweed extracts or granules fortified with mineral nutrients;
- potassium sulphate that is 100 percent water soluble;
- materials containing major nutrients and micronutrients for specific applications;
- special products containing amino acids, vitamins, humic acids, etc.

Fertilizers containing non-essential beneficial elements

Some cropping areas may need supplementation with beneficial mineral nutrients such as Na, Si, Co and Al. Some pastures may need additional nutrients such as the Co and Se required by grazing animals. All these and other materials cannot be sold as fertilizers in many countries because they may not feature in the definition and list of approved fertilizers in fertilizer legislation.

Sodium fertilizers

Na improves the growth of the so-called “Na-loving plants”, i.e. sugar beets, spinach, cabbage and barley. The Na concentrations in the leaves of such plants should be 1–3 percent, which is much higher than the Na concentration in cereals. The salt (NaCl) requirements of cattle make Na concentrations of about 0.2 percent in grass desirable. Fertilizers for improving the Na supply are sodium nitrate and multinutrient fertilizers with Na, such as special pasture fertilizer supplemented with 3-percent Na. Sodium chloride (NaCl) is only rarely used.

Silicon fertilizers

Silicate or silicic acid is beneficial to cereals because it improves the stalk stability and, thus, resistance to lodging. Although most soils contain enormous amounts

of silicates, its uptake is not always sufficient and may have to be improved by application of soluble silicate, a practice used in flooded-rice cropping in some areas. The quantities applied as Si fertilizers vary within wide limits. Silica fertilizers used are soluble silicic acid or soluble silicates and Si-containing phosphate fertilizers.

Cobalt fertilizers

Cobalt (Co) is beneficial for plants because it is essential for the N-fixing bacteria and blue green algae (BGA). Therefore, legumes and other N-fixing plants require a sufficient supply of Co, which is generally derived from the soil reserves. Co is mainly applied as cobalt sulphate (CoSO_4 with 21 percent Co). As the amount required on pastures is very small (50–80 g Co/ha), it is generally applied as an additive to phosphate fertilizers, e.g. 0.5 kg Co/ha can last for a long period. Because of the small amounts required, an alternative to Co fertilization is the direct supply of Co to animals together with ordinary salt.

Aluminium fertilizers

Al appears to be beneficial to only to a few plants, e.g. tea. Tea leaves contain 0.2–0.3 percent Al, which appears to promote growth. Where Al is considered to be deficient, aluminium sulphate [$\text{Al}_2(\text{SO}_4)_3$] can be added. However, aluminium sulphate acts mainly as a soil-acidifying agent and its favourable effect on some “acid-loving” plants such as blueberries may not be due to an improved Al supply but to the mobilization of some micronutrients as a result of acidification. For most crops, even small amounts of soluble Al ions are toxic.

Fertilizers with mineral nutrients for animals

For animal nutrition, additional elements may be required and these may have to be applied through fertilizer in some areas. Co has already been mentioned above. As Se deficiency has been discovered in animals grazing on pastures on soils that are poor in available Se, fertilizers containing Se have been developed. Generally, addition of Se to fertilizer is not recommended because the optimal supply range of Se is narrow and there may be a danger of toxicity on soils already well supplied. Polymer-coated Se fertilizers are available that reduce this risk. Little is known to date about the required “animal” nutrients Cr or vanadium (V) in soils.

Transportation, storage and mixing of solid fertilizers

The chemical composition and physical condition of a fertilizer as well as climate conditions directly affect its handling, storage, transportation and mixing with other fertilizers.

Effect of humidity

Many fertilizers absorb moisture from the atmosphere. This can adversely affect their physical condition and sometimes their quality. Moisture uptake by fertilizers is indicated by their hygroscopicity coefficient. This coefficient is obtained by

deducting the relative humidity of the air above a saturated solution from 100. The coefficient increases with increase in temperature, so that the risk of deterioration in fertilizer quality is greater in tropical than in temperate climate.

Another indicator is the critical relative humidity (CRH), which is the relative humidity at which a material starts absorbing moisture. The CRH is usually stated at 30 °C. The hygroscopicity coefficient and CRH values of some fertilizers as affected by temperature are provided in Table 19. The lower the CRH of a fertilizer is, the more hygroscopic it is. Such materials need special care during storage. CRH in the case of micronutrient fertilizers has not received much attention.

Some fertilizers, such as calcium nitrate and CAN, are extremely sensitive to moisture, harden and become liquefied. Only a few nitrogenous fertilizers, e.g. AS, retain their good flow properties at increased air humidity and, therefore, are very suitable for use in the tropics. The undesirable hardening of fertilizers is caused by crystal bridges being formed between the particles after wetting and drying.

Transportation and storage

Fertilizer particles should be spherical because spheres have maximum stability against pressure and make minimum contact with one another. Most fertilizer granules have a diameter of 2–4 mm, and uniformity in granule size is a precondition for good spreading and mixing of fertilizers.

The stability of the fertilizer granules is made vulnerable by the absorption of moisture from the air. Fertilizer granules may be conditioned during the production process to protect them from atmospheric moisture absorption. Coating fertilizer granules with non-hygroscopic conditioning substances such as lime, and diatomaceous earth, prevents granules from sticking together where humidity is high, prevents the collapse of granules under pressure, prevents the liquefaction of the fertilizer as a whole, and keeps the granules free flowing and dispersible during transportation, storage and application.

Fertilizer weight is important in transportation, storage and application. The bulk density (weight of the loosely filled fertilizer per unit volume) of most solid fertilizers is about 1 kg/litre. However, urea is considerably lighter with a bulk density of 0.7 kg/litre. Some fertilizers such as basic slag are exceptionally heavy with a bulk density of 2.0 kg/litre.

Care must be taken during transportation and storage not only to avoid detrimental effects to the fertilizers, but also to avoid any harm or injury to people

TABLE 19
Moisture absorption by fertilizers from the atmosphere

Fertilizer	Hygroscopic coefficient at		Critical relative air humidity at	
	20 °C	30 °C	20 °C	30 °C
Calcium nitrate	45	53	-	47
Ammonium nitrate	33	41	63	61
Sodium nitrate	23	28	-	72
Urea	20	28	79	74
Ammonium sulphate	19	21	81	81
Potassium chloride	14	16	-	84
Potassium sulphate	-	-	-	96
Di-ammonium phosphate	-	-	-	83

Sources: Finck, 1982, 1992; Tandon, 2004.

handling them. Some fertilizers become heated and create a fire hazard when they absorb moisture. Others are potentially explosive (e.g. AN), many are corrosive, and some may release harmful gases. Fertilizers are generally conditioned against such undesirable effects, but such conditioning is only possible to a certain extent. Regulations are generally issued at country level for the proper handling, storage and transportation of various fertilizers, especially in large quantities.

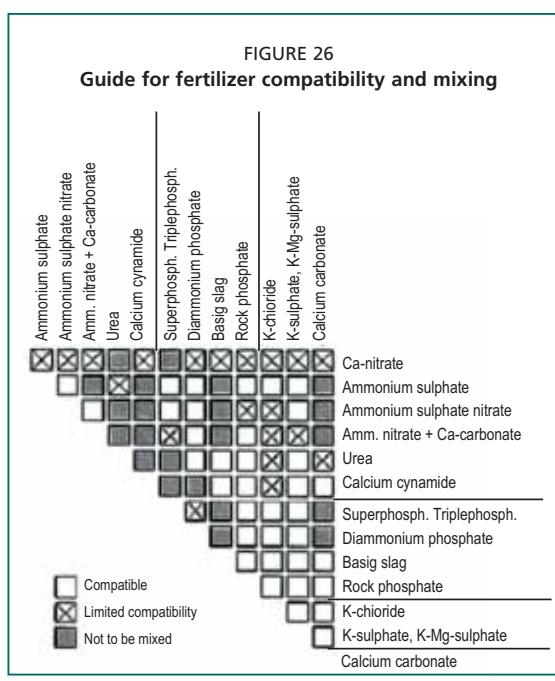
Bags made of plastic and paper (and laminated jute in some areas) are the usual containers for fertilizers. The 50-kg bags prevalent in developing countries often have to be carried manually. However, large farms may use large bags that contain 500–1 000 kg of material and require mechanical handling. Bulk transportation and storage of loose (bulk) fertilizers saves packing and handling labour, but requires suitable equipment for transport and protection against moisture during storage. Large farming enterprises are increasingly moving towards bulk fertilizers.

Mixing of solid fertilizers

As plants need several nutrients, fertilizers can be bought individually and distributed separately or blended together prior to spreading. There are several alternate ways to apply multiple nutrients. Mixing is generally not required when appropriate complex/compound fertilizers are selected. Several fertilizers can be mixed without problems (compatible fertilizers), but there are three chemical reasons for not mixing fertilizers indiscriminately:

- possibilities of losses of N by chemical reactions;
- possibilities of immobilization of water-soluble phosphate;
- possibilities of deterioration of distribution properties due to hygroscopicity.

The compatibility of fertilizers, allowing for these factors, is indicated in Figure 26.



Source: Finck, 2001.

Reactions of ammonium fertilizers after moisture absorption, with alkaline substances such as lime, etc., result in loss of N with ammonia escaping in gaseous form, CAN being an exception. Water-soluble phosphates should not be mixed with lime-containing or alkaline-acting fertilizers because insoluble and less available compounds are formed. Highly hygroscopic fertilizers are conditionally miscible, which

means that they should not be used in a mixture and stored but mixed only in dry weather shortly before application.

Bulk blending is a special type of fertilizer mixing in which only granulated products of fairly uniform size and density are used. Blended fertilizers are prepared by the mechanical mixing of two or more granular materials in defined proportions. Bulk blending originated in the United States of America and now dominates the fertilizer market in many areas. Often, a farmer has a bulk blend prepared according to the soil test report of the particular farm – a tailor-made, ready-to-use mixture. The main advantages to the farmers are:

- nutrients are supplied in ratios to suit the needs of particular soils and crops;
- the cost per unit of plant nutrient is generally low;
- the cost of transportation and spreading is low because of the high analysis of bulk blends.

However, the fertilizers used for mixing must be compatible both chemically and physically. The granules must be dry and strong so that they do not “cake” (stick together) and the granules must be similar in size in order to avoid segregation during mixing, transport and spreading. Common fertilizers used for bulk blending are DAP, MAP, TSP, AN, urea, MOP and special fertilizers to supply S, Mg and needed micronutrients.

The most important issues relate to the size and the density of granules. Granule size ranges from 1–4 mm in the United States of America and from 2–4 mm in Europe. The lower range is mainly caused by cheaply produced prilled urea with an average diameter of 1.5 mm, whereas phosphates and other common constituents exceed 2 mm in diameter. In addition to different granule size, large differences in bulk density may also cause segregation, the main problem being with urea, which has 30 percent lower density than most other fertilizers. Segregation of granules results in uneven distribution and erratic nutrient supply in the field. Another difficulty with bulk blending is mixing small amounts of micronutrients or herbicides with the much larger quantities of major nutrients.

ORGANIC SOURCES OF NUTRIENTS

Definition

Organic sources of nutrients are derived principally from substances of plant and animal origin. Partially humified and mineralized under the action of soil microflora, the organic sources act primarily on the physical and biophysical components of soil fertility. These sources cover manures made from cattle dung, excreta of other animals, other animal wastes, rural and urban wastes, composts, crop residues and even green manures. The term “bulky organic manure” is used collectively for cattle dung, FYM, composts, etc. because of their large bulk in relation to the nutrients contained in them. Concentrated organic manures, such as oilcakes, slaughterhouse wastes, fishmeal, guano and poultry manures, are comparatively richer in NPK.

General aspects

Organic sources of plant nutrients are used to varying extents in all countries. They may be used in the form in which they are obtained from the source or after having undergone varying degrees of processing. In most cases, the kinds of organic manures in use in a region are determined by the organic materials that are locally available or can be generated in the area, except for commercial organic fertilizers. According to surveys conducted by FAO through its various field projects (Roy, 1992), the main nutrient sources (in order of priority) in a number of countries are:

- Bangladesh: animal wastes, BNF (*Rhizobium*), green manuring;
- Burkina Faso: animal wastes, crop residues, BNF (*Rhizobium*);
- Democratic Republic of the Congo: crop residues, leaves of forest trees, BNF (*Rhizobium*);
- Guinea Bissau: crop residues, BNF (*Rhizobium* and *Azolla*);
- Indonesia: BNF (*Rhizobium*), recycling of legume crop residues, rice straw, animal wastes;
- Madagascar: animal wastes, crop residues (particularly rice straw), BNF (*Rhizobium* and *Azolla*).
- Nepal: in hill areas, animal wastes and BNF (*Rhizobium*); in terai areas, BNF (*Rhizobium*) and green manuring;
- Pakistan: animal wastes, BNF (*Rhizobium*), green manuring;
- Rwanda: animal wastes (in Butare and Gitarama regions), BNF (*Rhizobium*), crop residues;
- Sri Lanka: rice straw and legume crop residues, BNF (*Rhizobium*);
- Sudan: animal wastes, crops residues, BNF (*Rhizobium*);
- Thailand: BNF (*Rhizobium*), crop residues, agro-industrial wastes;
- United Republic of Tanzania: BNF (*Rhizobium*), crop residues;
- Zambia: animal wastes (certain areas in southern, western and central provinces), crop residues, BNF (*Rhizobium*).

Crop residues and green manures

Secondary products of crops, or auxiliary plants, are low-grade nutrient and soil-fertility improving resources. Composting can sometimes increase their value as a nutrient resource. Crop residues of legumes are richer in nutrients and have a low C:N ratio, which facilitates their mineralization compared with the residues of cereals. Similarly, processed residues such as oilcakes have a much higher nutrient content than conventional crop residues such as straw and stover.

Crop residues

Crop residues represent the bulk of the crop biomass left after removal of the main produce (grain, fruit, etc.) from the field. Most crops produce a voluminous amount of residues, e.g. straw, stalk, stubble, trash, and husks, which can have varying uses including as sources of plant nutrients either directly or after composting. Straw is produced in about the same and often higher amounts than grain (2–10 tonnes/ha)

and can serve several purposes on the farm where not used for fuel, roofing, cattle bedding or sold. Crop residues contain a substantial proportion of plant nutrients (Table 20).

However, the low N concentration of straw presents a special problem for its decomposition where the soil contains insufficient available N. Cereal straw has a C:N ratio of about 100:1 whereas ratios of below 25:1 are required for microbial decomposition in order to avoid N deficiency in the next crop. Such a growth-retarding effect can be avoided by adding 1 percent of mineral N to cereal straw. In spite of the low concentrations, as much as 125–250 kg K₂O can be added to the soil by 10 tonnes of cereal straw or 5 tonnes of oilseed rape straw. Being easily accessible to the farmer for use on the land, these have traditionally played an important role in maintaining soil productivity.

With some crops, such as sugar beets and sugar cane, large amounts of leaves are left on the field. They represent a large and valuable nutrient source, but their animal feed value is generally too high to be used as manures. Heavy leaf shedding before harvest is characteristic of jute plant and, in the process, large amounts of absorbed nutrients are returned to the soil.

Oilcakes

Oilcakes represent a special type of crop residue. These are the residues left behind after oil has been extracted from an oilseed. Table 21 provides a list of the average nutrient content of common oilcakes. Non-edible oilcakes can be used as manure, while edible oilcakes are used primarily as cattle feed. Oilcakes have a much higher nutrient content, particularly of N and P, than do normal crop residues, such as cereal straw or bulky organic manures. Owing to their low C:N ratio, these decompose at a faster rate in the soil to furnish available nutrients.

Green manures

Green manures represent fresh green plant matter (usually of legumes and often specifically grown for this purpose in the main field) that is ploughed in or turned into the soil to serve as manure. Several legume plants can be used as green manure crops. These are an important source of organic matter and plant nutrients, especially N where the green manure crop is a legume. Where feasible, green manuring is a key component of INM.

Green manure can either be grown *in situ* and incorporated in the field or grown elsewhere and brought in for incorporation in the field to be manured, in which

TABLE 20
Average nutrient content of some crop residues

Crop residues	Grain:straw ratio	Nutrient content (oven-dry basis)		
		N	P ₂ O ₅	K ₂ O
Rice straw	1:1.5	0.58	0.23	1.66
Wheat straw	1:1.5	0.49	0.25	1.28
Sorghum stalks	1:2.0	0.40	0.23	2.17
Pearl millet stalks	1:2.0	0.65	0.75	2.50
Maize stalks	1:1.5	0.59	0.31	1.31
Average pulses	1:1.0	1.60	0.15	2.00
Pigeon pea	1:2.5	1.10	0.58	1.28
Chickpea	1:1.0	1.19	n.a.	1.25
Sugar-cane trash	1:0.2	0.35	0.04	0.50

TABLE 21
Average nutrient content of some oilcakes

Oilcake sources	% N	% P ₂ O ₅	% K ₂ O	kg N + P ₂ O ₅ + K ₂ O/tonne of cake
Edible oilseeds				
Groundnut	7.29	1.65	1.33	103
Mustard	4.52	1.78	1.40	77
Rapeseed	5.21	1.84	1.19	82
Linseed ¹	5.56	1.44	1.28	83
Sesame	6.22	2.09	1.26	96
Cotton seed (decorticated)	6.41	2.89	1.72	110
Cotton seed (undecorticated)	3.99	1.89	1.62	75
Safflower (decorticated)	7.88	2.20	1.92	120
Safflower (undecorticated)	4.92	1.44	1.23	76
Non-edible oilseeds				
Castor	4.37	1.85	1.39	76
Neem (<i>Azadirachta indica</i>)	5.22	1.08	1.48	59
Mahua (<i>Madhuca indica</i>)	3.11	0.89	1.85	59
Karanj (<i>Pongamia glabra</i>)	3.97	0.94	1.27	62
Kusum (<i>Schleichera oleosa</i>)	5.23	2.56	1.37	92
Khakan (<i>Salvadora oleoides</i>)	4.32	2.45	1.24	80

¹ Edible and non-edible.

case it is referred to as green-leaf manuring. Not all plants can be used as a green manure in practical farming. Green manures may be: plants of grain legumes such as pigeon pea, green gram, cowpea, etc.; perennial woody multipurpose legumes, such as *Leucaena leucocephala* (*subabul*), *Gliricidia sepium*, and *Cassia siamea*; and non-grain legumes, such as *Crotalaria*, *Sesbania*, *Centrosema*, *Stylosanthes* and *Desmodium*. Because green manures add whatever they have absorbed from the soil, they in fact recycle soil nutrients from lower depths to the topsoil besides contributing to soil N through N fixation by the legume green manure crop. For major crops, some common green manures are:

- rice: sunnhemp, *Sesbania* and wild indigo (*Indigofera tinctoria*), *Azolla*;
- sugar cane: sunnhemp;
- finger millet: sunnhemp;
- wheat: sunnhemp;
- sorghum: sunnhemp, *Leucaena* (*Leucaena leucocephala*);
- banana: leaves of *Gliricidia sepium*;
- potato: sunnhemp, cowpea, cluster bean, lupin (*Lupinus albus*).

Green manures can add substantial amounts of organic matter and N as well as other nutrients. The bulk of the N input through leguminous green manures comes from BNF. Using rice culture as an example, this can range from 50 to 200 kg N/ha (Table 22). The nutrient contribution of a green manure crop is greatest where the entire green plant is ploughed in and incorporated in the soil. It is minimum but still appreciable where the grain of the legume is harvested and the straw or stover is ploughed in.

Green manure crops are often sown and incorporated in the field prior to planting a main crop such as rice, potato or sugar cane. Short-duration legumes

TABLE 22
Some green manure crops and their N contribution under optimal conditions

Crop	Scientific name	Suitable soil	Optimal	Duration in	N added
			temperature (°C)	days	(kg/ha)
Black gram	<i>Vigna mungo</i> L.	Well drained	15–35	70	60
Mung bean	<i>Vigna radiata</i> L.	Well drained	20–35	60–65	55
Cowpea	<i>Vigna unguiculata</i> L.	Well drained	10–38	45–60	60
Sesbania	<i>Sesbania rostrata</i> L.	Poorly drained	15–40	45–50	100
Sunnhemp	<i>Crotalaria juncea</i> L.	Poorly drained	12–35	45–50	120
Siratro	<i>Indigofera hirsute</i>	Well drained	15–35	100–120	80–90
Sesbania	<i>Sesbania bispinosa</i>	Wet to waterlogged	15–38	45–50	80
Cluster bean	<i>Cyamopsis tetragonoloba</i>	Marginal	12–35	-	80–90
Ipil-ipil	<i>Leucaena leucocephala</i>	Fertile	15–35	-	125 ¹
Gliricidia	<i>Gliricidia sepium</i>	Acid, low fertility	8–35	-	80–100 ¹

¹ N added through 4–5 tonnes of biomass.

Source: Pandey, 1991

can also be used as intercrops along with long-duration crops and used as green manures before or after picking the pods. After a few months of growth, generally at the beginning of flowering, the plants are cut and mixed into the soil. The gains in N with these short-duration legumes are generally of the order of 30–50 kg/ha N. There are limits to the use of green manuring under arid conditions because of the additional water requirement. Green manures and cover crops have an important place in plantations. Where grown on marginal lands and brought to fields, their nutrients can be considered as an external input, which is also the case where “weeds” such as water hyacinths are applied.

Farmyard manure and animal slurry

Farmyard manure (FYM)

FYM refers to the bulky organic manure resulting from the naturally decomposed mixture of dung and urine of farm animals along with the litter (bedding material). Average, well-rotted FYM contains 0.5–1.0 percent N, 0.15–0.20 percent P₂O₅ and 0.5–0.6 percent K₂O. The desired C:N ratio in FYM is 15–20:1. In addition to NPK, it may contain about 1 500 mg/kg Fe, 7 mg/kg Mn, 5 mg/kg B, 20 mg/kg Mo, 10 mg/kg Co, 2 800 mg/kg Al, 12 mg/kg Cr and up to 120 mg/kg lead (Pb). Often, fully or partially air-dried dung is used as FYM. FYMs can be used simply after air drying or after composting. Grazing animals return them directly to the soil as a natural nutrient supply, or the dry dung may be collected, stored and used as fuel or again as a manure in the desired area. A list of the average nutrient content of some organic manures including FYM and other organic manures is given in Table 23. The list includes manures derived from plants, animals and human wastes.

During storage, organic manure is partly decomposed by fermentation, which also produces valuable humic substances. Some losses of N as ammonia occur, but these can be reduced by the addition of about 2-percent water-soluble phosphate. Nutrient concentrations of fermented moist FYM (25 percent dry matter) depend

TABLE 23
Average nutrient content of bulky organic manures and composts

Type of manure	N	P ₂ O ₅ (%)	K ₂ O
Cattle dung	0.3	0.10	0.15
Sheep/goat dung	0.65	0.5	0.03
Human excreta	1.2–1.5	0.8	0.5
Hair and wool waste	12.3	0.1	0.3
Farmyard manure	0.5	0.15	0.5
Poultry manure	2.87	2.90	2.35
Town/urban compost	1.5	1.0	1.5
Rural compost	0.5	0.2	0.5

on feeding intensity, and vary over a wide range. In several tropical and subtropical areas such as South Asia, the FYM is applied preferentially before the rainy-season crops such as rice, maize and pearl millet rather than to wheat in the dry post-monsoon season. FYM is also frequently applied to potato, groundnut, sugar cane and vegetable crops in preference to crops such as wheat.

Animal slurry

In many developed countries, because of the shift towards intensive labour-saving animal production systems, many of which do not require bedding straw, there has also been a large output of animal slurry. In large areas, slurry is now the dominant animal manure although this can hardly be regarded as a desirable feature from an environmental and animal welfare point of view. Slurry from domestic animals consists of dung and urine, partly mixed with a small portion of straw and with small or large portions of water in order to improve its fluidity. It is a semi-liquid nutrient source that can be mechanically collected (pumped up to 12 percent dry matter), stored and distributed. The amounts of slurry produced per year are about 15–20 m³/cow (7–10 percent dry matter) and about 15 m³/pig unit (7 pigs) with 5–8 percent dry matter.

In regions with frozen or cold soils, slurry cannot be spread throughout the year. Therefore, it must be stored in large containers for up to several months. During this period, fermentation and conversion of urea to ammonia takes place and ammonia losses occur. Unpleasant odours may also be produced. Nutrient concentrations of fermented slurry with 5–10 percent dry matter are of the following order:

- cow slurry: 0.25–0.5 percent N, 0.3–0.5 percent K, 0.05–0.1 percent P;
- pig slurry: 0.4–0.8 percent N, 0.3–0.4 percent K, 0.1–0.2 percent P.

The main effect of slurry on crops is through its N supply. A large portion of N, about half with pig slurry, is ammonia N derived from decomposed urea. About half of the organic N is slow acting, the K fraction is mineral and the phosphate is mostly organic, but partly in mineral form (MgNH₄PO₄). The pH of slurry is about neutral.

Biogas plant slurry

The use of organic wastes for biogas production can be an important source of energy on the farm and also of manure. In India, many small-scale biogas production units have been established (Plate 1). Cattle dung is most commonly used as an input, mainly because of its availability. In addition to the animal and

human wastes, plant materials can also be used. Materials with a high C:N ratio could be mixed with those of a low C:N ratio to bring the average ratio of the composite input to a desirable level. In China, as a way of balancing the C:N ratio, it is customary to load rice straw at the bottom of the digester upon which latrine waste is discharged. Similarly, at Machan Wildlife Resort located in Chitawan District, Nepal, feeding the digester with elephant dung in conjunction with human waste enabled a balanced C:N ratio for the smooth production of biogas (Karki, Gautam and Karki, 1994). In the biogas production units, waste materials, are fermented under anaerobic conditions in a closed metal container (about 3 m³) for a few days. The resulting methane and hydrogen is used as fuel for cooking and lighting, and the residual material in slurry form can be used as manure either directly or as compost. The typical composition of biogas slurry is 1.4–1.8 percent N, 1.1–1.7 percent P₂O₅ and 0.8–1.3 percent K₂O. It is a useful organic manure. Effective small-scale biogas production is restricted to warm climates. It requires capital investment, maintenance and a considerable amount of manual work, but the energy gain can be considerable.

Compost

Although many organic waste products can be added directly into the soil, most of them have a better soil-improving effect after their decomposition through the composting process. The resulting mixed and improved products following decomposition are termed compost (Latin *componere* = mixing). Compost can be defined as an organic manure or fertilizer produced as a result of aerobic, anaerobic or partially aerobic decomposition of a wide variety of crop, animal, human and industrial wastes. Composting has a long tradition almost everywhere in the world. It was a central concept of early Chinese agriculture, but it has also been practised in India and Europe for centuries. Composts are generally classified as:

- Rural compost: This is produced from materials available on the farm and in other rural areas. The raw materials used can be straw, leaves, cattle-shed bedding, fruit and vegetable wastes, and biogas plant slurry. On average, it contains 0.5 percent N, 0.2 percent P₂O₅ and 0.5 percent K₂O. Rural compost primarily finds use on farms as a bulky organic manure.
- Urban or town compost: This refers to compost prepared from urban and industrial wastes, city garbage, sewage sludge, factory waste, etc. Its typical composition is 1.5–2.0 percent N, 1.0 percent P₂O₅ and 1.5 percent K₂O. Commercially prepared urban compost has been reported to contain 1 percent Fe, about 375 mg/kg Cu, 705 mg/kg Zn, 740 mg/kg Mn and small amounts of other micronutrients.



Plate 1
Biogas plant, example from India.

➤ **Vermicompost:** This is an important type of compost that contains earthworm cocoons, excreta, beneficial micro-organisms, actinomycetes, plant nutrients, organic matter, enzymes, hormones, etc. It is an organic fertilizer produced by earthworms and contains on average 0.6 percent N, 1.5 percent P₂O₅ and 0.4 percent K₂O. In addition to NPK, it is also a source of micronutrients, containing an average of 22 mg/kg Fe, 13 mg/kg Zn, 19 mg/kg Mn and 6 mg/kg Cu. It helps in cost-effective and efficient recycling of animal wastes (poultry, horse, piggery excreta and cattle dung), agricultural residues and industrial wastes using low energy.

Compost preparation

Composts are prepared through the action of micro-organisms on organic wastes such as leaves, roots and stubbles, crop residues, straw, hedge clippings, weeds, water hyacinth, bagasse, sawdust, kitchen wastes, and human habitation wastes. Virtually any biodegradable organic material can be composted. For making town or urban garbage compost, the organic wastes from households and other establishment should be carefully collected, separated from unsuitable materials and not contaminated with toxic substances. The main problem with compost prepared from urban wastes and garbage is the potential contamination with toxic substances that must be avoided.

A number of composting processes are in vogue in different parts of the world, comprising practices adopted as a convention, and the recently introduced methodologies for expediting the process that entail individual or combined application of treatments, such as: shredding and frequent turning, mineral N compounds, effective micro-organisms, use of worms, cellulolytic organisms, forced aeration and mechanical turnings. Conventional methods generally adopt an approach based on limited aerobic/anaerobic decomposition or one based on aerobic decomposition using passive aeration through measures such as little and infrequent turnings or static aeration provisions such as perforated poles/pipes. These processes take several months. On the other hand, using the recently developed techniques, rapid methods expedite the aerobic decomposition process and reduce the composting period to about four to five weeks. Most of these methods include a high temperature period, and this adds further value to the product by eliminating pathogens and weed seeds (FAO, 2003a).

During compost preparation, special supplements can be used such as some mineral N (1–2 kg N/m³ in order to obtain a C:N ratio of about 10–15:1, 2–3 kg CaCO₃/m³ for neutralization of surplus acids and possibly some PR for better P supply). By doing so, compost can be enriched and fortified. Phosphocompost is one such type of material where less reactive PR can be utilized effectively and the nutrient content of compost upgraded.

Nutrient content and quality standards

The nutrient content of a compost depends largely on the nutrient content of the wastes composted. The quality of composts varies widely. On average, compost

may contain 30–50 percent dry matter, 10–15 percent organic matter and the indicated amounts of plant nutrients. Ideally, compost should be rich in available plant nutrients, contain readily decomposable material and relatively stable humic substances, and have a crumbly structure, similar to a humus-rich topsoil. Composts are not only nutrient sources, but also effective soil amendments.

Quality standards define the composition and characteristics of compost and prescribe the maximum acceptable limits of undesirable elements. Such standards have been emerging gradually in the western world. Several European countries have adopted specific standards (Brinton, 2000). However, such standards are still in the process of development for most developing countries. Sometimes, a total minimum N, P₂O₅ and K₂O content of 5 percent is suggested as a requirement. One example relating to Bangkok is:

- minimum nutrient content: 1–3 percent N, 1.5–3 percent P₂O₅, 1–15 percent K₂O;
- moisture content: should not exceed 15–25 percent;
- organic matter: should be at least 20 percent C;
- C:N ratio: should be between 10:1 and 15:1
- pH: should be around neutral (6.5–7.5).

In garbage compost, harmful substances and pollutants such as toxic metals (e.g. Cd, Cr and Hg) or toxic organic compounds should be below the critical level (CL). Therefore, the compost materials need to be controlled for safe use in order not to endanger soil quality, plant growth, food quality or human health. Assuming that urban compost is used primarily for urban agriculture, the users are well advised to insist on proper compost quality in respect of toxic metals, even if the gain of cheap nutrients appears rather attractive. The principle should be that if the urban areas want to free themselves of waste materials, it is their responsibility to offer useful and safe products.

Recyclable waste products

The utilization of common waste products of plant and animal origin as sources of plant nutrients has been discussed above. In addition, several wastes or by-products of animal, human and industrial origin can also be used as sources of plant nutrients.

Waste products of animal origin other than excreta

A number of wastes derived from the bodies of domestic animals can be used as sources of plant nutrients. Important among these are various types of animal meals including bonemeal, which is a long-established source of phosphate for crop production. A list of the nutrient content of several such manures derived from the animal bodies is given in Table 24.

Animal meal is the common term used for the group of organic manures derived from animal wastes other than dung and urine (Table 24). Bonemeal is rich in P, others are rich in N. Bonemeal is an organic fertilizer derived from bones. Raw bonemeal consists of ground bones without any of the gelatin or glue removed.

TABLE 24
Average nutrient composition of some organic manures derived from the animal wastes

Manure	Nutrient content		
	N	P ₂ O ₅	K ₂ O
	(%)		
Meatmeal	10.5	2.5	0.5
Bloodmeal	10–12	1–2	1.0
Horn and hoof meal	10–15	1.0	-
Bonemeal (raw)	3–4	20–25	-
Bonemeal (steamed)	2–5	26–28	-
Fishmeal	4–10	3–9	1.8
Leather waste	7.0	0.1	0.2
Hair and wool waste	12.3	0.1	0.3

It contains at least 3 percent N and about 22 percent P₂O₅, of which about 8 percent is citrate soluble (available). It also contains variable amounts of micronutrients. Steamed bonemeal is obtained by treating crushed bones with steam under pressure in order to dissolve part of gelatine and then grinding the residue into a powder, which is then passed it through a sieve of 1-mm mesh size. It contains about 28 percent P₂O₅, of which about 16 percent is citrate soluble.

Waste products of human origin

Human excreta composed of faeces and urine along with domestic wastewater carried through sewers to the disposal points/treatment tanks is termed sewage. Sometimes, this may be further contaminated through industrial effluents (high in heavy metals). Sewage sludge is the end product of the fermentation (aerobic or anaerobic) of sewage. It is semi-solid and a useful organic manure. Activated sewage sludge refers to biologically active sewage sludge obtained by repeated exposure of the sewage to atmospheric oxygen, thus facilitating the growth of aerobic bacteria and other unicellular micro-organisms. In the process, it is improved for use on land.

The general composition of sewage sludge is 1.1–2.3 percent N, 0.8–2.1 percent P₂O₅ and 0.5–1.7 percent K₂O. It also contains Na, Ca, S, several micronutrients and toxic heavy metals (e.g. Al) in some cases. The typical nutrient content of activated sewage sludge is 5.8 percent N, 3.2 percent P₂O₅ and 0.6 percent K₂O. It also contains lesser and variable amounts of secondary and micronutrients and toxic heavy metals. Therefore, care has to be taken in deciding the optimal application rates depending on its composition.

Properly treated sewage effluent and processed products such as sewage sludge can serve as irrigation water and manure. The relative number of enteric pathogens in sewage effluent and sewage sludge depends on the type of sewage treatment. Primary treatment (consisting mostly of settling) removes 35–45 percent of pathogens while more than 95-percent pathogen removal is achieved by secondary treatment. Thus, the use of treated sewage for crop production minimizes the health risk. Chapter 7 discusses suggested cropping patterns for irrigation with untreated and treated sewage waters.

Waste products of industrial origin

Several industrial wastes and by-products can be used as sources of plant nutrients or as soil amendments after suitable processing. One such source is press mud or filter cake obtained from sugar factories.

Press mud is a by-product of sugar factories. It is the residue obtained by filtration of the precipitated impurities that settle out in the process of clarification of the mixed juice from sugar cane. The material has 55–75 percent moisture, is soft and spongy, light in weight and amorphous dark brown. It can readily absorb moisture when dry. Depending on the process used in the sugar factory, it can be either sulphitation press mud (SPM) or carbonation press mud (CPM). It contains 1–3 percent N, 0.6–3.6 percent P_2O_5 , 0.3–1.8 percent K_2O and 2.3 percent S.

SPM contains about 9 percent gypsum while CPM has 60 percent calcium carbonate. SPM is richer in plant nutrients compared with CPM. Thus, material from factories using a sulphitation process is a good source of S. Press mud from sugar factories using the carbonation process can find use as a liming material. Press mud can also be utilized after it is composted. It can be composted alone or with sugar-cane trash and animal dung. While preparing such compost, a 22.5-cm thick layer of SPM is arranged alternatively with a 22.5-cm thick layer of the yard sweepings consisting of cane trash, cattle dung and urine in pits for composting. It takes 6–8 months for the compost to be ready. The compost thus prepared has good manurial value, containing 1 percent N, 3 percent P_2O_5 , 1 percent K_2O and 8 percent CaO on a fresh-weight basis. Preparation of compost from distillery spent wash is also possible.

Commercial organic fertilizers

In their original state, waste products have a wide range of nutrient concentrations and are often difficult to handle. It is only reasonable and for the user's benefit that they should be processed into standardized nutrient sources. Such products are commercial organic fertilizers produced on a large scale, and they are much preferred by commercial growers to the original unprocessed waste materials.

Organic fertilizers can be defined as materials that have been prepared from one or more materials of a biological nature (plant/animal) and/or unprocessed mineral materials (lime, PR, etc.) that have been altered through controlled microbial decomposition into a homogenous product with a sufficient amount of plant nutrients to be of value as a fertilizer. Usually, they must contain a minimum of 5 percent nutrients ($N + P_2O_5 + K_2O$).

The raw materials used are processed through a process of drying, shredding, mixing, granulating, odour removal, pH modification, partial fermentation and composting, and always with proper hygienic control. This process provides standard products with certified concentrations of organic matter, a definite C:N ratio, guaranteed nutrient concentrations, and products without growth-impeding substances or sanitary problems. Finally, they are also easy to store and handle.

The types of commercial organic fertilizers, based on plant and/or animal residues, are often classified as follows:

- organic N fertilizers (at least 5 percent N, often higher);
- organic P fertilizers, mainly from bones (e.g. 25 percent P_2O_5);
- organic NP fertilizers (at least 3 percent N and 12 percent P_2O_5);
- organic NPK fertilizers (at least 15 percent of N, P_2O_5 and K_2O together);

- organo-mineral NP or NPK fertilizers, supplemented by mineral fertilizer or guano (e.g. NP with at least 5 percent each of N and P₂O₅, or NPK with at least 4 percent each of N, P₂O₅, and K₂O);
- organo-mineral fertilizers based on peat, but with nutrient supplements.

All these types of organic fertilizers are widely used, especially in gardening, where low nutrient concentrations and slow-acting N sources are preferred. In agriculture, they are applied mainly to vegetables. Some of these can be important inputs in organic farming.

Other types of organic inputs gaining popularity are those derived from seaweeds. These are red, brown or green algae living in or by the sea. Seaweeds like *Ascophyllum nodosum*, *Laminaria digitata*, and *Facus serratus*, contain gibberellin, auxins, cytokinin, etc. and are being used as liquid organic fertilizer with or without fortification with minerals in many countries. Their role is more of a plant-growth stimulant rather than of a nutrient supplier.

The term guano covers a special group of organic fertilizers derived from the excreta of, usually, small animals and includes materials such as bat guano, Peruvian guano, and fish guano. The general N content of guano can be 0.4–9.0 percent and total P₂O₅ can be 12–26 percent. Guano is found and used in certain areas only.

Application techniques for organic manures are discussed in Chapter 7.

BIOFERTILIZERS (MICROBIAL INOCULANTS)

Definition, classification and general aspects

Definition

Biofertilizer is a broad term used for products containing living or dormant micro-organisms such as bacteria, fungi, actinomycetes and algae alone or in combination, which on application help in fixing atmospheric N or solubilize/mobilize soil nutrients in addition to secreting growth-promoting substances. They are also known as bioinoculants or microbial cultures. Strictly speaking, although widely used, the term biofertilizer is a misnomer. Unlike fertilizers, these are not used to provide nutrients present in them, except in the case of *Azolla* used as green manure.

Classification

Biofertilizers can be grouped into four categories:

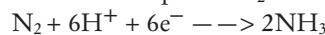
- N-fixing biofertilizers: These include the bacteria *Rhizobium*, *Azotobacter*, *Azospirillum*, *Clostridium* and *Acetobacter* among others; BGA or cyanobacteria and the fern *Azolla* (which works in symbiosis with BGA).
- P-solubilizing/mobilizing biofertilizers: These include phosphate-solubilizing bacteria (PSB) and phosphate-solubilizing micro-organisms (PSMs), e.g. *Bacillus*, *Pseudomonas* and *Aspergillus*. Mycorrhizae are nutrient-mobilizing fungi, also known as vesicular-arbuscular mycorrhizae or VA-mycorrhizae or VAM.
- Composting accelerators: (i) cellulolytic (*Trichoderma*); and (ii) lignolytic (*Humicola*).

- Plant-growth-promoting rhizobacteria (PGPR): Species of *Pseudomonas*. These do not provide plant nutrients but they enhance plant growth and performance.

General aspects

The most important biofertilizers used in agriculture are those that contain cultures of N-fixing organisms; next in importance are the cultures of P-solubilizing organisms.

BNF involves the conversion of nitrogen gas (N_2) into ammonia through a biological process (in contrast to industrial N fixation). Many micro-organisms (e.g. *Rhizobium*, *Azotobacter* and BGA) utilize molecular N_2 through the help of nitrogenase enzyme and reduce atmospheric N_2 to ammonia (NH_3):



BNF is a major source of fixed N for plant life. Estimates of global terrestrial BNF range from 100 to 290 million tonnes of N/year. Of this total, 40–48 million tonnes is estimated to be biologically fixed in agricultural crops and fields. The first commercial *Rhizobium* biofertilizer was produced as Nitragin in the United States of America in 1895. PSMs secrete organic acids that dissolve insoluble phosphate compounds. The first commercial P-solubilizing biofertilizer, Phospho-bacterin, was produced in the then Union of Soviet Socialist Republics.

Only N-fixing micro-organisms bring in net additional supplies of a nutrient (N) into the soil plant system. All other biofertilizers simply solubilize or mobilize the nutrients that are already present in soils. *Azolla* is unique in the sense that it acts as host to the N-fixing cyanobacteria, after which it is used virtually as a green manure. In the process, it adds not only the biologically fixed N but also the other nutrients absorbed from the soil and present in its biomass. While *Rhizobium* is legume specific, BGA and *Azolla* are specific to wetlands and, hence, useful in augmenting the N supply in flooded-rice cultivation.

Nitrogen-fixing biofertilizers

Rhizobium

Bacteria of the genus *Rhizobium* are able to establish symbiotic relationships with many leguminous plants, as a result of which the nitrogen gas (N_2) of the air is “fixed” or converted to ammonium ions that can be utilized by plants. These bacteria survive in the soil as spores. Where a root of a compatible species grows close to the spore, recognition occurs and symbiosis begins. The root hair curls and an infection thread appears from the spore and enters the root cells. The root responds by multiplying cells and these form the nodules on the roots that contain the bacteria. The root nodules act as the site of N fixation. The optimal temperature for their growth is 25–30 °C and the optimal pH is 6–7. Inoculation with *Rhizobium* is recommended for legumes (pulses, oilseeds and forages). On average, yield response to *Rhizobium* inoculation varies from 10 to 60 percent depending on the soil-climate situation and efficiency of the strain.

Not all species of *Rhizobium* can form a symbiotic relationship with all legumes and form nodules. There is generally high specificity between the bacteria and the host plant, called cross-inoculation groups. However, some plants can be infected by a range of *Rhizobium* species and form effective symbiotic association. In contrast to the root-nodule-forming *Rhizobium*, there is also the *Azorhizobium* bacteria, which is capable of forming root nodules as well as stem nodules on the tropical legume *Sesbania rostrata*. It is grouped under *Azorhizobium* in *Rhizobium* classification. The *Rhizobium* species that can form nodules and fix N with specific leguminous plants are:

- *Rhizobium ciceri*: It nodulates chickpea.
- *Rhizobium etli*: It nodulates beans.
- *Rhizobium japonicum* (now known as *Bradyrhizobium japonicum*): It nodulates soybean.
- *Rhizobium leguminosarum*: It nodulates peas, broad beans, lentils, etc.
- *Rhizobium lupini*: It nodulates *Lupinus* sp. and *Ornithopus* sp.
- *Rhizobium meliloti*: It nodulates *Melilotis* (sweet clover), *Medicago* (alfalfa) and *Trigonella* (fenugreek).
- *Rhizobium phaseoli*: It nodulates temperate species of *Phaseolus*.
- *Rhizobium trifolii*: It nodulates *Trifolium* spp.

Most soils contain these bacteria but their population may not be adequate or effective for forming productive associations with the crops sown. In such cases, the organisms must be artificially introduced into the system. This is generally done by mixing a culture/inoculum of the organism with the seed before sowing. Artificially prepared *Rhizobium* culture that is used for seed dressing of legumes before sowing to enhance the supply of N is referred to as the *Rhizobium* inoculant or biofertilizer. It is the most widely used biofertilizer in the world. Inoculation of grain legumes such as pulses is associated with an N gain of 20–40 kg N/ha. Application techniques of biofertilizers are discussed in Chapter 7.

Azotobacter

Azotobacter is a non-symbiotic, aerobic, free-living, N-fixing soil bacterium. It is generally found in arable soils but its population rarely exceeds 10^2 – 10^3 /g soil. Its six species are: *Azotobacter armeniacus*, *A. beijerinckii*, *A. chroococcum*, *A. nigricans*, *A. paspali* and *A. vinelandii*. Unlike *Rhizobium*, inoculation with *Azotobacter* can be done for a wide variety of crops. Grain yields obtained from plots untreated with fertilizer N but inoculated with N-fixing bacteria are similar to yields obtained from the application of 20–35 kg N/ha.

Azotobacter also synthesizes growth-promoting substances, produces group B vitamins such as nicotinic acid and pantothenic acid, biotin and heteroauxins, gibberellins and cytokinin-like substances, and improves seed germination of several crops. Both carrier-based and liquid-based *Azotobacter* biofertilizers are available. It is recommended as a biofertilizers for cereals and horticultural crops including flowers and vegetables. Its application is usually done through seed treatment, seedling treatment or soil application (described in Chapter 7).

Azospirillum

Azospirillum, a spiral-shaped N-fixing bacteria, is widely distributed in soils and grass roots. Major species of *Azospirillum* are *Azospirillum brasiliense* and *Azospirillum lipoferum*. It can fix 20–50 kg N/ha in association with roots. It also produces hormones such as indole acetic acid (IAA), gibberellic acid (GA), cytokinins and vitamins.

Acetobacter

Acetobacter is a rod-shaped, aerobic, N-fixing bacteria. *Acetobacter diazotrophicus* is an N-fixing bacteria found in the roots, stems and leaves of sugar cane with the potential to fix up to 200 kg N/ha. It is capable of growth at pH 3. It can also solubilize insoluble forms of P. Inoculation with *Acetobacter* is recommended for sugar cane.

Blue green algae

BGA are photosynthetic, unicellular, aerobic, N-fixing algae. They are also known as cyanobacteria and are used primarily as a biofertilizer in flooded-rice culture. More than 100 species of BGA are known to fix N. Commonly occurring BGA are *Nostoc*, *Anabaena*, *Aulosira*, *Tolyphothrix* and *Calothrix*. These are used as biofertilizer for wetland rice (paddy) and can provide 25–30 kg N/ha in one crop season, or up to 50 kg N/ha/year. The BGA also secrete hormones, such as IAA and GA, and improve soil structure by producing polysaccharides, which help in the binding of soil particles (resulting in better soil aggregation). BGA are also used as a soil conditioner and, through mat formation, they protect the soil against erosion.

Soil pH is the most important factor in determining BGA growth and N fixation. The optimal temperature for BGA is about 30–35 °C. The optimal pH for BGA growth in culture media ranges from 7.5 to 10, and its lower limit is about 6.5–7. Under natural conditions, BGA growth is better in neutral to alkaline soils. BGA need all the plant nutrients for their growth and N fixation. N fertilizers generally inhibit BGA growth and N fixation. Adequate available P should be present in the floodwater as P enhances BGA growth and N fixation. Consequently, P deficiency causes drastic reduction in BGA growth and, hence, in N fixation. Mo is another essential nutrient for the growth and performance of BGA.

The inoculum of BGA can be prepared in the laboratory or in the open fields. The open-air soil culture method is simple, less expensive and easily adaptable by farmers. BGA are multiplied in shallow trays or tanks with 5–15 cm standing water in 4 kg soil/m². A thick BGA mat is formed on the soil surface in about 15 days and the tray is allowed to dry in the sun. BGA flakes are collected and stored for use (described in Chapter 7).

Azolla

Azolla is another N-fixing biofertilizer of specific interest in rice cultivation. *Azolla* itself is a fern. N fixation is carried out by the cyanobacterium *Anabaena azollae* in the leaf cavities of *Azolla*. The most common species of *Azolla* are:

- *Azolla pinnata*: This is the most important species. It is widespread in the Eastern Hemisphere, tropical Africa, Southeast Asia, etc. Of its two forms, *Azolla pinnata* var. *pinnata* and *Azolla pinnata* var. *imbricata*, *pinnata* is more common. Its favourable temperature is 20–30 °C.
- *Azolla caroliniana*: A multitolerant species of *Azolla*, it is pest resistant, shade tolerant and thrives under a wide temperature range.
- *Azolla filiculoides*: It is cold tolerant (-5 °C), and heat sensitive (exceeding 30 °C).
- *Azolla microphylla*: It is heat tolerant but cold sensitive.
- *Azolla nilotica*: Reported to occur in the Nile River in Africa.

On average, dry *Azolla* contains 2.08 percent N, 0.61 percent P₂O₅, 2.05 percent K₂O, and has a C:N ratio of 14:1. It is known to accumulate significant amounts of K. *Azolla* can accumulate 30–40 kg K₂O/ha from irrigation water in the paddy-field. The N-enriched *Azolla* biomass is incorporated into the soil, thus providing the N fixed by the cyanobacteria and all other nutrients absorbed by the fern from the soil and irrigation water. Thus, it is more of a green manure than a conventional biofertilizer. One crop of *Azolla* can provide 20–40 kg N/ha to the rice crop in about 20–25 days.

Azolla requires all the essential plant nutrients for normal growth. Because of its aquatic nature, these elements must be available in the soil water. The deficiency of any one element adversely affects its growth and N fixation. In these respects, *Azolla* behaves like an agricultural crop. P is a key element and its deficiency results in poor growth, pink or red coloration, root curl and reduced N content. Temperature is a key factor that limits the growth of *Azolla* and 25–30 °C is optimal for most species. A pH of 5–8 is optimal although *Azolla* can survive in the pH range of 3.5–10.0. The inoculum for *Azolla* biofertilizer is in the form of dry spores. Application details are provided in Chapter 7.

Phosphate-solubilizing biofertilizers

There has been much research conducted on the use of organisms to increase P availability in soils by “unlocking” P present in otherwise sparingly soluble forms. These microbes help in the solubilization of P from PR and other sparingly-soluble forms of soil P by secreting organic acids, and in the process decreasing their particle size, reducing it to nearly amorphous forms. The earliest known commercial P-solubilizing biofertilizer, Phospho-bacterin, contained *Bacillus megatherium* var. *phosphaticum*. Phosphate-solubilizing organisms include:

- bacteria: *Bacillus megatherium* var. *phosphaticum*, *Bacillus polymyxa*, *Bacillus subtilis*, *Pseudomonas striata*, *Agrobacterium* sp.; *Acetobacter diazotrophicus*, etc.;
- fungi: *Aspergillus awamori*, *Penicillium digitatum*, and *Penicillium belaji*;

- yeast: *Saccharomyces* sp., etc.
- actinomycetes: *Streptomyces* sp., *Nocardia* sp.

In addition to bacteria, the fungus *Penicillium belaji* has been shown to increase P availability from native soil and PR sources in calcareous soils. The responses to soil inoculation of such biofertilizers have been reported, but they are low, averaging about 10 percent, and extremely variable. Based on present evidence, it seems unlikely that inoculation with micro-organisms will contribute significantly to plant P nutrition in the foreseeable future. However, in some countries such as India, the P-solubilizing biofertilizers are becoming popular, ranking next in importance only to the N-fixing *Rhizobium* inoculants. Usually, more than one type of organism is used while preparing a P-solubilizing biofertilizer.

Nutrient-mobilizing biofertilizers

The most prominent among nutrient mobilizers in the soil are the soil fungi mycorrhizae. These form symbiotic relationships with the roots of host plants. These are of two types:

- Ectomycorrhizae: These form a compact sheath of hyphae over the surface of roots of a limited number of plant such as *Pinus* and *Eucalyptus*.
- Endomycorrhizae: These penetrate the roots and grow between the cortical cells. They produce storage “vesicles” (“saclike” structures) between the cells and multibranched “arbuscules” within the cells. Hence, the name vesicular-arbuscular mycorrhizae (VAM). They also produce thin hyphae that grow out up to 2 cm from the root surface.

VAM are ubiquitous in most soils and naturally infect most plants. Responses to field inoculation with VAM are rare except in crops such as onions that have no root hairs to facilitate P uptake and require a rapid supply of P. Responses to soil inoculation do not occur where there is ample P in the soil. Because mycorrhizae cannot be cultured in the same way as rhizobia, commercial inoculation is not possible at this stage. Where inoculation is required, soil from infected plants is used. Application of organic manures stimulates VAM.

The relationship between mycorrhizae and plant roots is useful in improving the capability of plants for soil exploration and nutrient uptake. VAM have been associated with increased plant growth and with enhanced accumulation of plant nutrients, mainly P, Zn, Cu and S, primarily through greater soil exploration by the mycorrhizal hyphae. Out of their special structures, the arbuscules help in the transfer of nutrients from the fungus to the root system and the vesicles store P as phospholipids. Thus, the exploratory capacity of the root system is improved far beyond the zones of nutrient-depleted soil that may surround the root.

Being an obligate symbiont, mycorrhiza inoculum can be supplied in the form of infective soil, infected roots and soil sievings. However, infective roots and growth medium from pot cultures open to the atmosphere can become contaminated with pathogens (fungi, bacteria and nematodes). Mycorrhizae have to be cultured using a particular host. Onions, sorghum and other grasses are

suitable hosts. Such cultures are used as inoculum in the form of seed pellets, granules or as such in plastic bags and can be stored at 4 °C for 2–3 months.

SOIL AMENDMENTS

Only very few soils are “by nature” ideal substrates for plant growth. Much effort has been devoted to improving “problem” soils. Generally, the chemical properties of soils are easier to improve than are the physical ones. With increasing intensity of cropping, many methods of soil improvement have become available and proved profitable.

Of the chemical soil properties, the soil reaction (pH) of many soils must be optimized in order to create favourable conditions for plant growth, nutrient availability and to eliminate the harmful toxic substances. Optimizing soil pH is a precondition for the success of nutrient management for crop production. It entails either raising the pH of acid soils or lowering the pH of alkaline soils. Among the soil physical properties, the improvement of soil structure is of great concern to farmers. The texture of sandy, clayey or stony soils may also be improved but to a very limited extent.

Amendments for raising the soil reaction (liming)

Soil acidity is reflected primarily in an increase in H⁺ ions and a corresponding decrease in the basic cations. Carbonates (lime), hydroxides and some other basic acting substances are able to neutralize soil acids. The purpose of liming is primarily the neutralization of the cause of soil acidity (H⁺ ions and Al³⁺ in very acid soils), thus raising the pH value.

Ca and Mg compounds are mainly used for the amelioration of acid soils. Most liming materials are obtained from limestone deposits that were formed in seas of earlier geological periods. The resulting limestone may be from inorganic precipitates or from carbonate shells. It can range from physically very soft material to very hard rock. Limestone reserves are immense in the form of calcitic and dolomitic mountains. However, there may be regional deficiencies of liming materials as many tropical regions that need them are distant from such deposits.

Liming materials

Common liming materials are:

- Calcium carbonate. It generally contains 75–95 percent CaCO₃, corresponding to 42–53 percent CaO (the reference basis for lime effect). A magnesium carbonate (MgCO₃) concentration of more than 5 percent is useful. The particle size of hard limestone must be less than 1 mm and that of soft material (chalk) less than 4 mm.
- Calcium magnesium carbonate (dolomite). Its different types contain 15–40 percent MgCO₃ and 60–80 percent CaCO₃. These products are suitable for acid soils that are also Mg deficient.
- Quicklime (CaO) and slaked lime Ca(OH)₂. These are quick-acting amendments for the neutralization of soil acidity, but they are generally

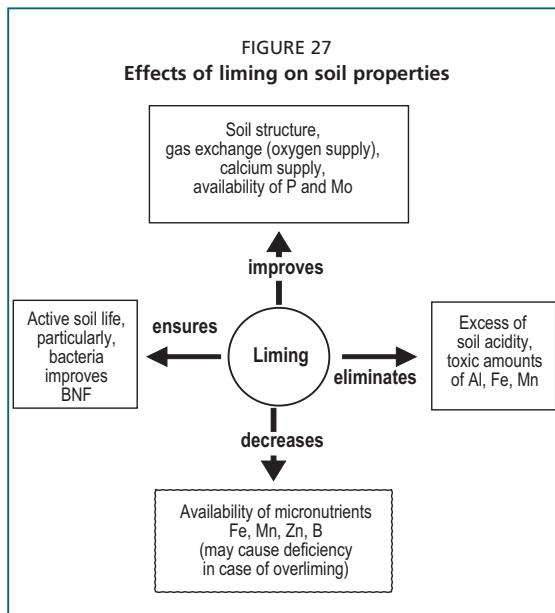
more expensive than natural limes. They have a special role in certain applications, e.g. creating a well-structured soil surface layer for sowing sugar-beet seeds.

The most common liming material is ground natural limestone (CaCO_3) with a definite fineness, depending on the hardness of the rock. The harder the rock is, the finer is the grinding needed to obtain equal efficiency. Carbonate limes act slowly because they are only slightly soluble in water and must be dissolved into neutralizing forms. Their solubility in dilute hydrochloric acid (HCl) has recently been accepted as a measure of their reactivity for evaluation purposes. Some have substantial amounts of Mg (an advantage for Mg-deficient soils), whereas others contain small amounts of Mn. Lime amendments not only decrease soil acidity but also have other positive effects (Figure 27).

A special kind of lime amendment is marl (“lime earth”). This was used in ancient Greek and Roman agriculture. Marl is a mixture of soil material with 10–30 percent calcium carbonate and it is found in the top few metres of soils of glacial origin. It was rediscovered in Europe in the eighteenth century and used extensively for amelioration of the then acid soils. The mining and distribution of marl requires high labour costs. Lime formed from red marine algae is particularly soft and also contains some B.

Selection of liming materials

In principle, all liming materials can be applied on all soils, but the choice of a material depends mainly on soil texture, local availability and cost. Medium to heavy soils (texture of loam and clay) can be neutralized rapidly with quicklime. However, to maintain the optimal reaction, slow-acting carbonates are more suitable. In coarse-textured soils (sand and loamy sand), carbonate lime is preferable because of the lower risk of overliming where an excessive amount is applied or where the distribution is not uniform. Another aspect of the choice is the presence of by-products. Some limes also contain nutrients other than Ca, some clay minerals, organic matter or micronutrients, which makes them more valuable for sandy soils. The most important of such products is Mg. Application details of liming materials are discussed Chapter 7.



Many industrial by-products have a neutralizing effect on soil acidity and can be used as amendments. Some are easily mobilizable, such as silicates mixed with quicklime. Others contain a certain amount of phosphate and Mg, which makes them suitable for amelioration of acid soils that are also deficient in P and Mg. Press mud from sugar factories using the carbonation process is rich in lime and can be used to improve acid soils. Several PRs also have acid-neutralizing properties. Fly ash is a powdery residue remaining after coal has been burned (as in a thermal power station). It has received considerable attention as a soil amendment for ameliorating acid soils. However, caution is needed to avoid undue accumulation of B, Mo, Se and soluble salts in fly-ash-treated soils.

Amendments for alkaline and alkali soils

Intentional acidification to lower the soil pH may be required on alkaline soils for various reasons. These include removal of negative factors such as micronutrients deficiencies, and removal of excess Na. Soils that have been overlimed may require acidification to improve the availability of Fe, Mn and Zn. Other situations may require an acidic environment for certain crops such as tea. As already mentioned, a certain degree of acidification can be obtained by using N fertilizers that produce an acidic effect where these are cost-effective. However, on soils with a high buffering capacity, this effect may be small.

Amendments for effective acidification are either acids or those that produce acids after decomposition in soil. The most effective substance is diluted sulphuric acid, but its use is technically difficult, costly and inconvenient. In alkali (sodic) soils, the objective is to remove excess exchangeable sodium ions (Na^+) from the rootzone and the undesirable soil dispersion in order to create a favourable environment for plant growth. Common amendments are:

- ferrous sulphate (FeSO_4), which yields acid after hydrolysis with water;
- elemental S, which yields acid after oxidation by bacteria to sulphate;
- iron pyrite (FeS_2), which yields sulphuric acid after decomposition (also used for alkali soils);
- calcium sulphate or gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), for alkali soils.

The amount of acidifying amendments required depends on the lime content of the soil and other properties. One tonne of S decomposes about 3 tonnes of calcium carbonate. A special test for acidity requirement is recommended in order to avoid unwanted damage. The amount of amendments required for reclaiming alkali soils depend on soil pH and soil texture, with higher amounts needed in soils with very high pH (10 and above) and a high clay content. It is now known that reclamation of only the top 10–15 cm of alkali soils is sufficient. This results in considerable savings in terms of the cost of amendments, water and labour.

Amendments for improving soil texture and structure

In addition to adequate nutrient supplies, a precondition for optimal plant growth is an optimal water supply, adequate aeration of the soil and root penetrability, both in the topsoil and subsoil. Soil physical properties can be improved by creating better

soil structure as a precondition for optimal water supply and aeration, and a more favourable soil texture for water retention, root growth and proliferation.

Amendments for soil texture improvement

Light sandy soils lack adequate fine clay particles, whereas heavy clay soils lack enough coarse particles. The consequences of extremely coarse or fine particle sizes are a low potential for natural structure formation. The obvious measures for altering the particle size composition of soils are to supply clay particles to light soils, and sand particles to heavy soils. The key issue is the quantity to be applied and its practical feasibility. The addition of 1 percent of a mineral component is equivalent to adding 30 tonnes/ha of material to the 0–20-cm layer of a topsoil weighing 3 000 tonnes/ha. Thus, increasing the clay content of a sandy soil from 4 to 10 percent in order to convert it into a loamy sand requires 6×30 or 180 tonnes/ha of clay material. This would involve substantial transportation costs even if such material were available free of charge in the vicinity of the field. Where suitable sand or clay material is present in the subsoil, it may potentially be brought to the surface through deep cultivation in order to reduce this problem. The disadvantages associated with extremes of soil texture can to some extent be overcome by the use of all available organic material and crop residues.

Amendments for soil structure improvement

An important measure for improving the structure and opening up the subsoil is correct tillage. However, this results in only temporary improvement, and it should be supplemented by creating favourable conditions for the structure-forming processes in the soil. Several amendments have been developed specifically to improve soil structure. These are usually called soil conditioners and are applied to increase the WHC and resistance to erosion of soils. In fine-textured heavy soils, these are used for creating a crumb structure, chiefly for better aeration.

Many commonly used materials, such as lime and organic manures, improve soil structure indirectly. The following substances contribute to the bonding of the soil particles (which creates good crumb structure):

- inorganic or mineral matter: oxides, lime, silicate coatings, and gypsum;
- organic materials: slimy “glues” (polysaccharides, especially polyuronides) produced by microbes, the hyphae of fungi and humic substances derived from the formation of clay humus complexes (the conditions for which are especially favourable in the intestines of small soil animals, particularly earthworms).

In some soils, it may be necessary to improve or supplement natural crumb formation. This can best be achieved by increasing the saturation of the exchange complexes with Ca through the application of liming materials or gypsum (where liming is not possible). The addition of gypsum may be more beneficial for heavy-textured soils but the quantities required are considerable (2–10 tonnes/ha).

Organic soil conditioners imitate the natural bonding among particles and their effect may be sustained for several years. Various polymer dispersions and

powders of polymers with long-chain and filamentary molecules are used. One of the first of these soil conditioners was Krilium (which is based on polyacrylic acid) in the United States of America. Other products developed were derived from polyvinyl acid, e.g. VAMA (polyvinyl acetate and maleic acid anhydride) or polyvinyl propionate. These substances are sprayed on the mechanically loosened soil or spread as powders and “rained in” with water. The quantities applied vary between 0.1 and 2 tonnes/ha and the effect is sustained for several years. However, the considerable cost per unit area restricts their application to horticultural and other high-value crops.

Substances that loosen the soil can improve fine-textured heavy soils. One such product is Styromull, which consists of flocs of polystyrene foam. The foamed material is chemically inert and does not react with the soil. It resists rot and does not become internally moist as it consists of cells filled with air. The addition of these 4–12-mm flocs increases permeability to water and aeration considerably. The amount required is about 10 percent by volume or 1–2 m³/100 m² area. This is an expensive procedure and the risk of polystyrene washing into waterways has to be considered. Improved soil aeration can also be achieved by adding coarse rock powder and crop residues. Special soil conditioners are used to loosen fine-textured heavy soils and for stabilizing coarse-textured soils. The mineral soil conditioners used are ammonium iron sulphate and sodium hydrosilicate colloids. These are sprayed onto the soil surface and worked into the topsoil at the rate of 1–1.5 tonnes/ha.

Sandy soils often dry out easily. However, this can be prevented by adding water-absorbing/storing substances. For example, Hygromull consists of flocs of foamed plastic urea formaldehyde resin. This has fine open pores in the 4–12-mm flocs where water is stored up to 60–70 percent of the volume. Only about 5 percent is decomposed annually with a corresponding part of the N component (30 percent) being mineralized. The quantities applied are 2–4 m³/100 m². Again, this is expensive.

Various plant nutrients and their sources can be utilized for optimizing nutrient supplies and managing them for higher efficiency. Chapter 6 deals with strategies for optimizing plant nutrition and Chapter 7 provides some guidelines for nutrient management, including application techniques.

Chapter 6

Optimizing plant nutrition

GENERAL ASPECTS

The goal of optimal plant nutrition is to ensure that crop plants have access to adequate amounts of all plant nutrients required for high yields. The nutrients have to be present in the soil or provided through suitable sources in adequate amounts and forms usable by plants. The soil water should be able to deliver these nutrients to the roots at sufficiently high rates that can support the rate of absorption, keeping in view the differential demand at various stages of plant growth. Optimal plant nutrition must ensure that there are no nutrient deficiencies or toxicities and that the maximum possible synergism takes place between the nutrients and other production inputs.

The ideal state of optimal plant nutrition may not be easy to achieve in open fields. However, it is possible to come close to it by basing nutrient application on the soil fertility status (soil test), plant analysis, crop characteristics, production potentials and, finally, the practicality and economics of the approach. Proper selection of nutrient sources and their timing as well as method of application are equally important. In the end, farmers should be able to maximize their net returns from investment in all production inputs including nutrient sources. In many countries, farmers do not have the financial resources or access to credit for fully implementing the constraint-free package of recommended inputs. Thus, for optimal plant nutrition to be of value to most farmers, it should also aim to optimize the benefit at different levels of investment.

In spite of all theoretical and practical progress towards efficient crop production, it still depends on some uncontrollable and unforeseeable factors, and on interactions among nutrients and inputs. Decisions on fertilization are normally based on certain assumptions of future events, e.g. weather conditions, that may be assumed to be normal but may not turn out to be so. Because of this general uncertainty, many essential data can only be estimated approximately. Thus, some misjudgements can hardly be avoided – neither by farmers toiling at a low yield level nor by those striving for high yields, and not even in scientific experiments, observations and advice.

From the farmers' point of view, optimization of nutrient supply appears difficult considering the many aspects of nutrient supply, uptake, requirements and use efficiency. This is facilitated by improving soil fertility in total, which means, to a large extent, not only offering an optimal uninterrupted nutrient supply but also providing generally favourable preconditions for their effective use. Therefore, extension personnel and farmers are well advised to maintain

the fertility of their soils in a good, functioning state and to improve it continuously.

Chapters 4 and 5 contain the background information for optimizing plant nutrition. Chapter 7 provides the principles and guidelines for nutrient management, followed by some examples of general crop recommendations in Chapter 8. Optimal plant nutrition must lead to balanced and efficient use of nutrients and, thus, also to minimal adverse effects on the environment. This is made possible by combining optimal nutrient supplies with best management practices. Towards achieving this goal at field level, farmers must have access to adequate resources, timely and quality advice, and remunerative market prices for their produce.

Balanced crop nutrition

Plants need a proper supply of all macronutrients and micronutrients in a balanced ratio throughout their growth. The basics of balanced fertilization are governed by Liebig's law of the minimum (discussed in Chapter 3). Formerly, it was rightly concluded that, on many soils, the application of N without simultaneous supplies of phosphate and K made little sense. Today, in view of multiple nutrient deficiencies and increasing costs of crop production, fertilization with N or NPK without ensuring adequate supplies of all other limiting nutrients (S, Zn, B, etc.) makes little sense and, in fact, becomes counterproductive by reducing the efficiency of the nutrients that are applied.

Therefore, in view of the widespread occurrence of other nutrient deficiencies, the scope and content of balanced fertilization itself has changed. It now includes the deliberate application of all such nutrients that the soil cannot supply in adequate amounts for optimal crop yield. There is no fixed recipe for balanced fertilization for a given soil or crop. Its content is crop and site specific, hence the growing emphasis on SSNM. The SSNM approach for rice production systems is in various stages of development in several countries, e.g. China, India, Indonesia, Philippines, Senegal, Thailand and Viet Nam. With particular reference to irrigated rice, the SSNM approach involves the following steps (Dobermann and Witt, 2004):

1. Field-specific estimation for the potential indigenous supplies of N (INS), P (IPS) and K (IKS) and diagnosis of other nutritional disorders in the first year.
2. Field-specific recommendations for NPK use and alleviation of other nutritional problems.
3. Optimization of the amount and timing of applied N. Decisions about timing and splitting of N applications are based on: (i) 3–5 split applications following season-specific agronomic rules tailored to specific locations; or (ii) regular monitoring of plant N status up to the flowering stage, using a chlorophyll meter or leaf colour charts.
4. Estimation of actual grain yield, stubble (straw) returned to the field, and amount of fertilizer used. Based on this, a P and K input–output balance

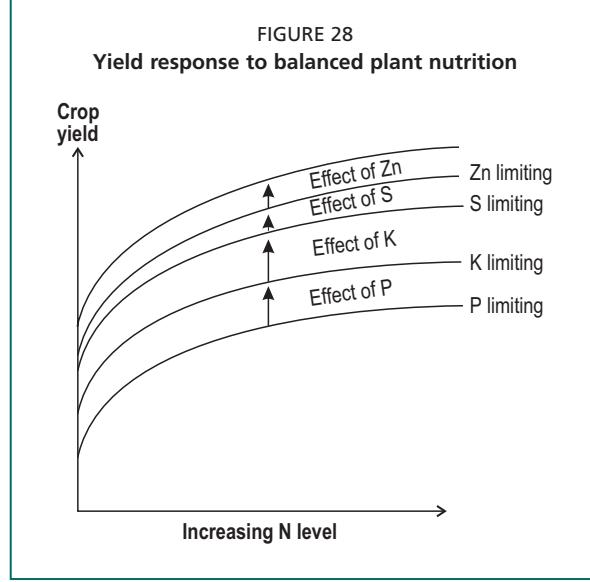
is estimated and used to predict the change in IPS and IKS resulting from the previous crop cycle. The predicted IPS and IKS values are then used to develop fertilizer recommendations in the subsequent crop cycle.

Depending on the situation, some examples of the components of balanced fertilization (nutrients whose application is needed) for different situations are:

- many intensively cropped irrigated areas: N, P, K, Zn and S, or N, P, S and Zn, or N, P and Zn, or N, P, K and Zn;
- coconut in light soils and in root-affected (wilt) areas: N, P, K and Mg;
- immature rubber plantation: N, P, K and Mg;
- mature rubber plantation: N, P and K;
- many areas under oilseeds: N, P, K and S, or N, P and S, or N, P, Zn and S, or N, P, S and B;
- fruit trees in alkaline, calcareous soils: N, P, K, Zn, Mn and Fe;
- cabbage, cauliflower and crucifers in many areas: N, P, K, S and B;
- legumes in acid soils: N, P, K, Ca and Mo;
- newly reclaimed alkali soils in early years: N and Zn;
- high-yielding tea plantation: N, P, K, Mg, S and Zn.

All other factors being optimal, any deficiency of one plant nutrient will severely limit the efficiency of other nutrients (Figure 28). Imbalanced nutrient supply results in mining of the soil nutrient reserves. It can also lead to losses of the nutrients supplied, such as N, by reducing their rate of utilization. Imbalanced availability of nutrients also encourages luxury consumption of nutrients supplied in excess. This decreases the productive efficiency of all applied nutrients. Imbalanced fertilization is inefficient, uneconomic and wasteful, and it should be avoided.

Balanced crop nutrition is not the same as balanced fertilization. The latter should make the former possible. For example, only soils equally poor in available N, P and K should be fertilized with these three nutrients in balanced amounts. This can best be done using soil-test and crop removal data. Where a soil is rich in one nutrient, fertilization should be directed to the deficient nutrients in order to make balanced crop nutrition possible. Thus, the goal is not balanced fertilization as such but balanced crop nutrition through balanced nutrient application in order to supplement those nutrients that are deficient in the soil.



Source: FAO, 1998 (modified to include S and Zn).

TABLE 25
Nutrient-related constraints in relation to increasing yield,
example of tea in south India

Productivity (kg/ha of made tea)	Limiting factors
Below 800	None
800–1 000	N and K
1 000–2 000	N, P, K, Zn and lime
2 000–3 000	N, P, K, Zn and liming with materials containing Mg
3 000–4 000	N, P, K, Zn, Mg, Si, B, liming, and transport processes within the soil
More than 4 000	N, P, K, Zn, Mg, Si, Mo, B, liming, and transport processes within the soil

Source: Tandon and Ranganathan, 1988.

Crop nutrition in relation to yield

The requirements for optimal nutrition depend very much on the type of crops grown and the yield level to be attained. The expected yield level largely determines the amount of external nutrient input necessary. It is not so much the yield per se that determines this, but the amount of nutrients removed from the field with the crop produce and the efficiency

of applied nutrients. The replacement of nutrients removed at a given yield level is sometimes used to maintain soil fertility on soils that have been built up to a desired level. Here, two sets of fertilizer application norms are used, one for fertility buildup, and the other for fertility maintenance, specifically in case of P.

As the yield goals move up, the “nutrient basket” demanded by the crop also becomes more varied and complex. A soil may have sufficient fertility to support a crop of 2 tonnes/ha but may not be able to support a crop of 5 tonnes/ha on its own. At high yields, it does not remain simply a question of providing N or NPK. This had already been seen in many intensively cropped areas that, in the early 1960s, needed only N. Over a period of time, it became necessary to apply N + P, then N + P + K or N + P + Zn. Now many areas require the application of at least five nutrients (N, P, K, S and Zn) from external sources in order to sustain high yields. This is well illustrated by the example of nutrient needs for increasing levels of tea productivity in south India (Table 25). The principle is the same and holds good for all crops, only the nutrient package differs.

Prevention of excessive fertilization

Overfertilization or excessive fertilization is wasteful and is to be avoided. It goes against the concept of optimizing crop nutrition and also reflects poor application of scientific findings and unprofessional marketing practices. It can also have adverse impacts on the environment. Where high rates of water-soluble fertilizers are applied to crops, transient salt damage to the roots of young sensitive plants should be avoided. Moreover, the excessive or luxury supply of one nutrient can create antagonistic effects that disturb the nutrient balance. For example, high doses of K reduce Mg uptake even where there is a satisfactory Mg supply. Overfertilization not only reduces crop yield and produce quality but also produces suboptimal economic returns.

The optimal application rate of a nutrient can be seen as the cut-off point that is not to be exceeded in most cases. A farmer can continue to benefit from suboptimal rates of application although the benefit is always smaller than at the optimal level. In this respect, fertilizers and other nutrient carriers differ from

inputs such as pesticides, which must be applied at a certain critical dosage to be effective. Thus, nutrient application is more flexible, similar to water application, as it enables farmers to operate over a wide range of rates based on their resources and the availability of inputs.

While overfertilization with nutrients such as P can produce significant residual benefits for the following crop, excessive application blocks the farmer's capital unnecessarily. Overfertilization with N invariably leads to lower nitrogen-use efficiency, greater possibility of lodging, pest and disease attack, greater N losses and negative impacts on the environment. Overfertilization with micronutrients can lead to their toxicity, which in many cases is difficult to ameliorate.

From fertilization to integrated nutrient management (INM)

Owing to the widespread use of fertilizers containing N, P and K and their effectiveness in increasing crop yields the world over, the term fertilization has become synonymous with the use of commercial NPK fertilizers. This is a rather narrow outdated concept, which does no justice to the wide field of plant nutrition or to the implications concerning undesirable environmental effects. Although fertilizers have benefited from more systematic and well-defined production and marketing, there are other effective sources of plant nutrients. These include crop residues, organic manures, various recyclable wastes and biofertilizers. Farmers all over the world have been using organic manures for a very long time. Chapter 5 has described various sources of plant nutrients. Diverse nutrient sources can be used in an integrated manner to meet the external nutrient supplies of any cropping system. Towards this end, scientifically, there is no conflict between mineral and organic sources of plant nutrients.

Definition

Although the term fertilization still has a place to describe the actual nutrient supply to crops, it is now gradually being replaced by the wider concept of integrated plant nutrition system (IPNS) or INM. Fertilizers are and will continue to be a major component of INM for producing high yields of good quality on a sustained basis in many parts of the world.

The basic concept underlying IPNS/INM is the maintenance or adjustment of soil fertility/productivity and of optimal plant nutrient supply for sustaining the desired level of crop productivity (FAO, 1995). The objective is to accomplish this through optimization of the benefits from all possible sources of plant nutrients, including locally available ones, in an integrated manner while ensuring environmental quality. This provides a system of crop nutrition in which plant nutrient needs are met through a pre-planned integrated use of: mineral fertilizers; organic manures/fertilizers (e.g. green manures, recyclable wastes, crop residues, and FYM); and biofertilizers. The appropriate combination of different sources of nutrients varies according to the system of land use and the ecological, social and economic conditions at the local level.

The need for INM

The need to adopt a wider concept of nutrient use beyond but not excluding fertilizers results from several changing circumstances and developments. These are:

- The need for a more rational use of plant nutrients for optimizing crop nutrition by balanced, efficient, yield-targeted, site- and soil-specific nutrient supply.
- A shift mainly from the use of mineral fertilizers to combinations of mineral and organic fertilizers obtained on and off the farm.
- A shift from providing nutrition on the basis of individual crops to optimal use of nutrient sources on a cropping-system or crop-rotation basis.
- A shift from considering mainly direct effects of fertilization (first-year nutrient effects) to long-term direct plus residual effects. To a large extent, this is accomplished also where crop nutrition is on a cropping-system basis rather than on a single-crop basis.
- A shift from static nutrient balances to nutrient flows in nutrient cycles.
- A growing emphasis on monitoring and controlling the unwanted side-effects of fertilization and possible adverse consequences for soil health, crop diseases and pollution of water and air.
- A shift from soil fertility management to total soil productivity management. This includes the amelioration of problem soils (acid, alkali, hardpan, etc.) and taking into account the resistance of crops against stresses such as drought, frost, excess salt concentration, toxicity and pollution.
- A shift from exploitation of soil fertility to its improvement, or at least maintenance.
- A shift from the neglect of on-farm and off-farm wastes to their effective utilization through recycling.

These realizations have led to the widening of the concept of fertilization to one of INM, where all aspects of optimal management of plant nutrient sources are integrated into the crop production system. For developing INM practices, the cropping systems rather than an individual crop, and the farming systems rather than the individual field, are the focus of attention. In contrast to organic farming, INM involves a needs-based external input approach, taking into account a holistic view of soil fertility. One of the aims of INM is to obtain high yields and good product quality – in a sustainable agriculture with practically no damaging effects on the environment. INM offers great possibilities for saving resources, protecting the environment and promoting more economical cropping.

Components of INM

The concept of INM is that of a nutrient integrator and not one of nutrient excluder. The major components of INM are the well-known and time-tested sources of plant nutrients with or without organic matter (Chapter 5). These primarily include:

- mineral fertilizers containing both major nutrients and micronutrients;

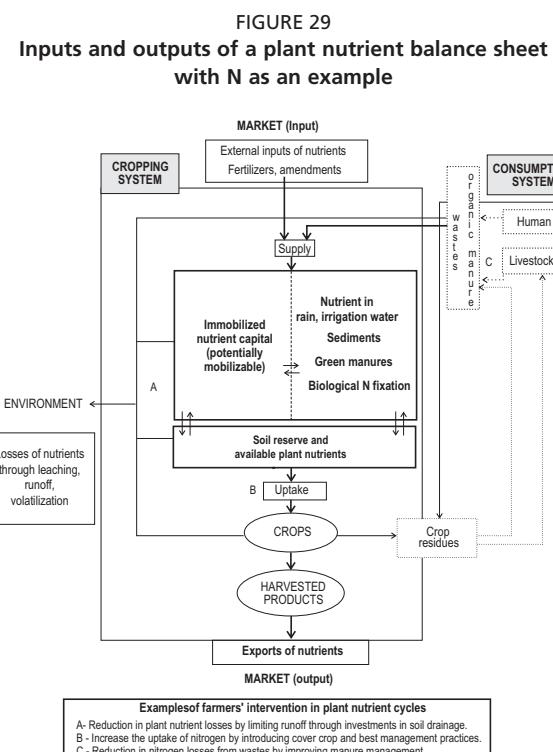
- suitable minerals such as PR, pyrites and elemental S;
- crop residues;
- green manures and green leaf manures;
- various organic manures of plant, animal, human and industrial origin;
- recyclable wastes from various sources with or without processing provided these do not contain harmful substances or pathogens above permissible limits;
- animal slurries and biogas plant slurry;
- microbial inoculants (biofertilizers);
- commercial organic fertilizers.

The main features and adoption of INM

The main concern of a farmer is to obtain sustainable high yields under local production conditions. The farmer can profit from the adoption of modern cropping principles, of which sustainability and INM play an important role.

At the farm level, INM aims to optimize the productivity of the nutrient flows through the soil/crop/livestock system during a crop rotation (Figure 29). A balance sheet can be established for every nutrient. However, owing to the complexity involved, only the major nutrients N, P and K are generally considered. The efficiency of a production system depends on the importance of crop uptake versus the total supply of nutrients. High losses of nutrients limit the efficiency. Exploitation of plant nutrient stocks is permissible as long as it does not affect the supply of nutrients and the general status of soil fertility.

Moreover, INM improves the production capacity of a farm through the application of external plant nutrient sources and amendments, and the efficient processing and recycling of crop residues and on-farm organic wastes. It empowers farmers by increasing their technical expertise and decision-making capacity. It also promotes changes in land use, crop rotations, and interactions between forestry, livestock and cropping systems as part of agricultural intensification and diversification. INM involves risk



Source: FAO, 1998.

management (risk reduction) and enhances the synergy between crop, water and plant nutrition management.

During the adoption of INM, special attention should be given to sources of nutrients that may be mobilized by the farmers themselves (manures, crop residues, soil reserves, BNF, etc.). Minimization of losses and replenishment of nutrients from both internal and external sources are of major interest. While INM strives for the integrated application of diverse inputs, the use of organic sources cannot replace the use of mineral fertilizers. Although the effects of organic inputs go beyond the nutritional aspects, by contributing to improving soil physical properties and to a better efficiency of fertilizer use, the recycling of organic materials does not suffice to fully replenish the nutrients that are removed by crop harvests. Therefore, an increased and more efficient use of mineral fertilizers in most developing countries is required in the medium term (FAO, 1995).

In countries where a wide concept of crop nutrition beyond fertilization has been recognized, many INM guidelines have already been considered but not adopted on a large scale. In countries with intensive crop production where modern codes of good agricultural practice have been accepted, there is a trend towards better plant nutrient management or integrated crop management systems. This results in a more efficient nutrient use, leading partly to a reduced fertilizer input – even if it means a slightly lower yield level.

BASIC INFORMATION FOR OPTIMIZING CROP NUTRITION

Initial soil fertility status

Balanced nutrient application is a key controllable factor for optimizing crop nutrition on any field. The information on which nutrients to apply and at what rates should be based on a good soil test report. It is assumed that the soil test has already been validated by a high degree of correlation with crop response to the application of the concerned nutrient. The nutrient application rates based on soil tests can be for one optimal yield level or for pre-set yield targets. The optimal yield level is normally the profit-maximizing yield and not the highest achievable yield per se. Thus, the information on soil fertility status as provided by soil test data is a basic piece of information for optimizing crop nutrition for most nutrients, with the possible exception of N. In the absence of reliable soil tests for N, N application in many advanced agricultural areas is optimized on the basis of soil characteristics, growth conditions and crop removal of N at expected yield levels.

Soil testing as a tool for estimating the available nutrient status of soils continues to be a problem area in spite of more than 60 years of intensive research. Analysis of the experience in North America shows that even the best soil test calibration explains less than one-third of the variability in crop response to added nutrients. This has implications for the optimization of nutrient application rates. Factors such as soil texture, yield potential, specific weather conditions and differences between crop cultivars make it difficult to obtain a clear relationship between soil

test and crop responses (Bruulsema, 2004). Ideally, the soil test value should be able to capture residual effects of previous nutrient applications. Chapter 4 has discussed evaluation of soil fertility for determining optimal application.

Amelioration of problem soils

Of the many types of problem soils, acid and alkali soils are mentioned here as examples. Amelioration of problem soils is a precondition for optimizing plant nutrition. This is because such soils cannot make the best use of the nutrients applied in the absence of suitable amendments. In fact, soil amendments should precede nutrient application. Once the soils have been amended, the crops grown on them can make efficient use of the nutrients applied and high yields can be obtained on a sustained basis.

Amendment of alkali soils

Alkali soils can be amended with several materials (Chapter 5). Gypsum is the most commonly used amendment. The main purpose of these amendments is to remove excess exchangeable Na from the rootzone, which also results in an improvement in soil physical properties. Once the soil has been amended, near normal rates of N (120–150 kg N/ha) can be applied to rice or wheat. In the initial years after reclamation, optimal productivity can be obtained with the application of N and Zn. Many alkali soils have a high level of soluble P, so that P application is required only after several years (5–10) depending on the crop. Green manuring such soils is useful for optimizing plant nutrition and sustaining productivity (Tyagi, 2000). Without the amelioration of such soils, yields are low and nutrient application is wasteful.

Knowledge of the tolerance of crops to alkalinity can be usefully applied for selecting the most suitable crops for such conditions. Table 26 summarizes the relative tolerance of several crops to exchangeable sodium percentage (ESP). A sound strategy for optimizing plant nutrient use in such soils would be to treat the soil with a suitable amendment and select a salt-tolerant crop cultivar. Selection of a tolerant crop is also beneficial where the soil cannot be amended adequately.

Amendment of acid soils

Acid tropical soils represent a large block of potentially arable soils. Management strategies for them must accomplish the dual task of neutralizing excess acidity (making the soil profile hospitable to plant roots) and correction of nutrient deficiencies. The basis for optimizing plant nutrition in such soils is provided by neutralization

TABLE 26
Relative tolerance of crops to exchangeable sodium percentage in the soil

Range of ESP*	Crops
10–15	Safflower, black gram, peas, lentil, pigeon pea
15–20	Chickpea, soybean, maize
20–25	Groundnut, cowpea, onion, pearl millet, clover
25–30	Linseed, garlic, cluster bean, lemon grass, palmarosa, sugar cane, cotton
30–50	Wheat, rapeseed mustard, sunflower, oats, cotton, tomato
50–60	Barley, beets, <i>Sesbania</i> , para grass, Rhodes grass
60–70	Rice, Karnal grass

* Relative crop yields are only 50 percent of the maximum in the alkalinity range indicated.

Source: Tyagi, 2000; Gupta and Abrol, 1990.

TABLE 27

The impact of lime and fertilizer application to maize over 40 years in an acid soil at Ranchi, India

Input applied ¹	Grain		Cost ² of input	Value ² of grain	Net returns	
	Yield (kg/ha)	Response			(Rs/ha)	(BCR)
1956–1969						
0	600	-	-	-	-	-
N	1 500	900	462	4 500	4 038	8.7
NP	2 100	1 500	1 176	7 500	6 324	5.4
NPK	2 400	1 800	1 503	9 000	7 497	5.0
NPK + lime	3 000	2 400	1 943	12 000	10 057	5.2
1970–1979						
0	500	-	-	-	-	-
N	300	-200	1 155	-	Loss	Loss
NP	1 500	1 000	2 339	5 000	2 661	1.1
NPK	2 000	1 500	2 733	7 500	4 767	1.7
NPK + lime	3 600	3 100	3 173	15 500	12 327	3.9
1980–1989						
0	500	-	-	-	-	-
N	30	-470	1 155	-	Loss	Loss
NP	100	-400	2 615	-	Loss	Loss
NPK	300	-200	3 135	-	Loss	Loss
NPK + lime	4 100	3 600	3 595	18 000	14 405	4.0
1990–94						
0	500	-	-	-	-	-
N	20	-480	1 155	-	Loss	Loss
NP	50	-450	2 615	-	Loss	Loss
NPK	100	-400	3 135	-	Loss	Loss
NPK + Lime	4 800	4 300	3 575	21 500	17 925	5.0

¹ Average application rate of N + P₂O₅ + K₂O in kg/ha were 44–44–44 (1956–1968), 104–73–53 (1969–1979) and 110–90–70 from 1980 onwards. Lime applied once in 4 years as per LR.

² Economics based on prices in Rs/kg of 10.5 for N, 16.22 for P₂O₅, 7.43 for K₂O, 5.00 for maize grain and Rs440/year for lime (US\$1 = Rs44).

Source: Sarkar, 2000.

of soil acidity, improving base status of the subsoil, and planting crop species that can tolerate excess Al.

The amendment of acid soils creates favourable conditions for optimizing plant nutrient use by neutralizing excess acidity and improving the availability of several major nutrients and micronutrients (Figure 17). As a rule, soil amendment, in this case liming, must precede fertilizer application. Without correcting soil acidity, no amount of balanced nutrient application can result in high yields or superior NUE. Thus, plant nutrition is a component of and not a substitute for good management. In many cases, the investment made in costly fertilizers may give very small returns or even result in a loss after a short period of initial success.

Results of a long-term field experiment in the acid red-loam soil at Ranchi in eastern India evidence this clearly (Sarkar, 2000). In this field experiment, which started in the mid-1950s, plots were treated either with N, N + P, N + P + K or N + P + K + liming. The scenario over a period of four decades has been summarized in Table 27 and can be described as follows:

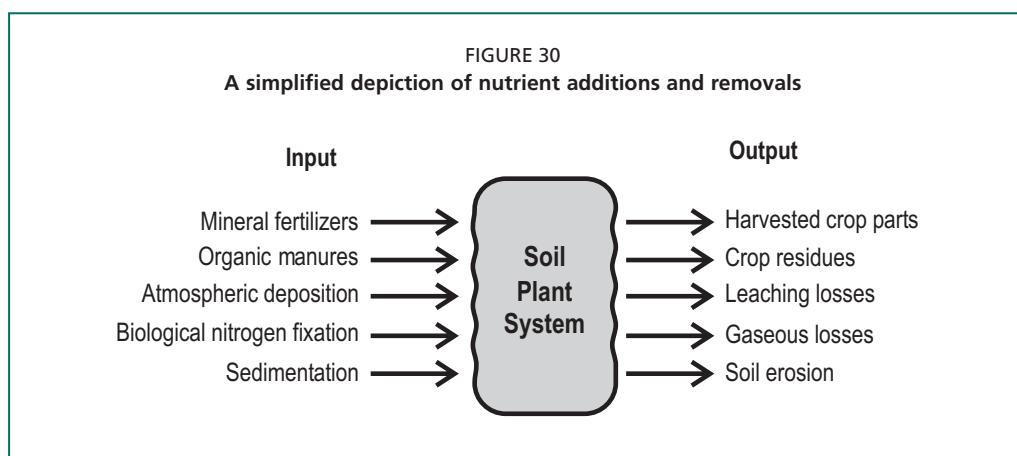
- Stage I (1956–1969): Application of all nutrients (N, P and K) with or without lime increased maize yields and was profitable with the highest profits coming from NPK + lime application.
- Stage II (1970–79): Application of N alone could not increase maize yield any more and investment in N was a total loss. This was partly because in these plots, P and K were being depleted (becoming deficient) and partly because the use of N (as ammonium sulphate) progressively made the soil more acid. Applying NPK raised maize yields and profits. However, the soil acidity was becoming a more dominant constraint than nutrient deficiencies. Not only did the response rates to fertilizer (even “balanced”) decline, the difference between NPK and NPK + lime plots widened in terms of yields, response and economic returns.
- Stage III (1980–89): Increasing soil acidity was now deciding the fate of crop growth and no amount of “balanced fertilization” was of help. Application of any nutrient could not even produce as much grain as the unfertilized control plot (500 kg/ha). The limed + NPK treated plots increased maize yield by 3 600 kg/ha as compared with a decrease of 200 kg/ha with NPK. Net returns in the NPK + lime treated plots were nearly Rs18 000/ha (US\$410/ha) while NPK application (without lime) resulted in a total loss of money spent on fertilizers.
- Stage IV (1990–94): The same story as in Stage III was repeated with even more unfavourable effects of fertilizer without lime (maize yield 100 kg/ha with optimal NPK application) in contrast to 4 800 kg/ha with the same amount of NPK but applied after liming.

The example in Table 27 is just one out of many examples available to illustrate the crucial role of soil amendments for optimizing crop nutrition.

Nutrient recovery by crops and nutrient removal

An assessment of nutrient additions, removals and balances in the agricultural production system yields useful practical information on whether the nutrient status of a soil (or area) is being maintained, built up or depleted. It also gives insights into the level of fertilizer-use efficiency and the extent to which externally added nutrients have been absorbed by the crop and utilized for yield production. It can also forewarn about nutrient deficiencies that may aggravate in the coming years and need attention.

Figure 30 provides a simplified depiction of nutrient additions and removals. Most of the arrows in this figure also include nutrient recycling to a varying extent. For example, on the input side, part of mineral fertilizers, particularly N, S and K, can leach down but be recycled to the extent the groundwaters are pumped for irrigation. Over a toposequence, the nutrient loss for one field can become the nutrient gain for another field (and farmer). Nutrients from organic manures can enter the plant after mineralization. Atmospheric deposits (N and S) originate from N in the air, gaseous losses and pollution. Similarly, inputs through sedimentation have often been brought in by erosion from higher levels (output) and, in many



Source: Smaling, 1993.

cases, are actually intersite transfers (30 percent of the soil and nutrients moved by water erosion end up in the sea, the remaining 70 percent stay on the land).

On the output side of Figure 30, harvested crop parts and crop residues both yield valuable organic manures. Most estimates of nutrient removal by crops (from the soil) are overestimates because nutrient removal is often equated with nutrient uptake. This is not the case in many situations. The proportion of nutrients taken up that constitutes nutrient removal can vary from less than 10 percent (as in cardamom) to about one-third (as in coffee) to as much as 90 percent as in several field crops when only stubbles and roots are left behind.

Estimates of nutrient input and output allow the calculation of nutrient balance sheets both for individual fields and for geographical regions. It is a bookkeeping exercise, similar in many ways to keeping a bank account. The extent of nutrient removals from the soil system can provide useful information for optimizing crop nutrition.

Nutrient uptake and removal

At harvest time, plants contain considerable amounts of nutrients in plant parts such as grain, straw, stalks, beets, tubers and fruits, but only a small portion is contained in the roots. Depending on which plant parts are harvested and removed, the nutrients contained in them are removed from the field. In many developing countries where grain crops are harvested manually, the entire nutrients present in grain and straw or stover may be removed from the field. In the case of green manure crops, all plant nutrients in the biomass are returned to the soil and no nutrients are removed, except in situations where legume pods are removed for consumption. In fact, net soil enrichment takes place because of the contribution from BNF in case of leguminous green manures.

Knowledge of nutrient removal from the field is essential for calculating the amounts of nutrients taken away through harvested crops and for establishing a

nutrient balance sheet. The nutrient removal data are more useful where computed on the basis of one basic unit of a harvest, e.g. 1 tonne of grain or 1 tonne of straw, so that the total removal at a certain yield level can be calculated easily. Average removal data are useful where nutrients have not been absorbed in excess. Where there is luxury consumption of nutrients, the corresponding removal data can be misleading. In intensive agriculture, N and K data tend to be biased upwards because of this factor. Therefore, larger than necessary amounts may be determined for the replacement of nutrient removals.

Nutrient uptake

Nutrient removal data quoted in the literature for the same crop can vary over a wide range. Table 28 provides some average nutrient removal data. These are based primarily on North American conditions. Nutrient removal data for Indian conditions, representing the tropical and subtropical areas, are presented in Tables 29 and 30 for general and comparative information. These data pertain to uptake per tonne of main produce and include the nutrients present in the by-produce as well. A substantial proportion of N in legumes (pulses, soybean, groundnut, forages, etc) originates from BNF, assuming a satisfactory level of nodulation and N fixation.

Nutrient uptake by crops can vary from less than 50 kg/ha to more than 1 000 kg/ha depending on the crop, variety, the nutrient, its availability, growth conditions and the biomass produced. Major nutrients constitute the bulk of the nutrients taken up. For example, the total amount of nutrients absorbed by wheat and rice (paddy) per tonne of grain production is about 82 kg and 74 kg, respectively. Out of this, N and K₂O alone account for about 75 percent. On an element basis, S uptake is generally similar to P uptake. The six micronutrients taken together add up to about 1 kg/ha (Tandon, 1999).

Higher production through higher cropping intensity also results in substantially higher nutrient uptake, which can range from 400 to 1 000 kg N + P₂O₅ + K₂O/ha/year. The share of N, P₂O₅ and K₂O in nutrient uptake is generally 35 percent N, 17 percent P₂O₅ and 48 percent K₂O, in the ratio 1.0:0.5:1.4. Thus, every tonne of N removed is accompanied by the removal of 0.5 tonnes P₂O₅ and 1.4 tonnes K₂O on average.

In addition to major nutrients, a grain production level of 10 tonnes/ha through a rice–wheat rotation (6 tonnes paddy + 4 tonnes wheat) can absorb about 3–4 kg of Fe or Mn, 0.5 kg Zn, 200–300 g of Cu or B but only 20 g Mo. Thus, at the same production level, the uptake among nutrients by a crop can vary by more than 10 000 times (260 kg K vs 20 g Mo). Within the group of micronutrients itself, the uptake of Fe and Mn can be 200 times that of Mo. For successful crop production, the crop must be able to access and absorb the indicated nutrients whether these are 150–200 kg of N or K₂O or 15–20 g of Mo.

Nutrient uptake by a crop depends on a large number of factors, both controllable and otherwise. This is why large variations are encountered for a given nutrient or for a given crop even under similar conditions. Nutrient uptake

TABLE 28
Nutrient content of some major crop products and residues

	Nutrient content								
	N	P ₂ O ₅	K ₂ O	Ca	Mg	S	Cu	Mn	Zn
Grains									
Barley (grain)	18.2	7.8	5.2	0.5	1.0	1.6	0.016	0.016	0.031
Barley (straw)	6.7	2.2	13.4	3.6	0.9	1.8	0.004	0.143	0.022
Corn (grain)	16.1	6.3	4.8	0.2	1.0	1.2	0.007	0.011	0.018
Corn (stover)	9.9	3.7	14.4	2.6	2.0	1.4	0.005	0.149	0.030
Oats (grain)	19.5	7.8	5.9	0.8	1.2	2.0	0.012	0.047	0.020
Oats (straw)	5.6	3.4	17.9	1.8	1.8	2.0	0.007		0.065
Rye (grain)	20.9	6.0	6.0	1.2	1.8	4.2	0.012	0.131	0.018
Rye (straw)	4.5	2.4	7.4	2.4	0.6	0.9	0.003	0.042	0.021
Sorghum (grain)	14.9	7.4	4.5	1.2	1.5	1.5	0.003	0.012	0.012
Sorghum (stover)	9.7	3.0	14.2	4.3	2.7				
Wheat (grain)	20.8	10.4	6.3	0.4	2.5	1.3	0.013	0.038	0.058
Wheat (straw)	6.0	1.5	10.4	1.8	0.9	1.5	0.003	0.048	0.015
Hay									
Alfalfa	20.1	4.5	20.1	12.5	2.3	2.1	0.007	0.049	0.047
Bluegrass	13.4	4.5	13.4	3.6	1.6	1.1	0.004	0.067	0.018
Coastal Bermuda	22.3	5.1	19.3	2.7	1.8	1.8	0.001	0.036	0.027
Cowpea	26.8	5.6	17.9	12.3	3.4	2.9		0.145	
Fescue	17.2	8.3	23.6	5.0	1.7	2.6			
Orchard grass	22.3	7.4	27.9	5.0	1.9	2.6			
Red clover	17.9	4.5	17.9	12.3	3.0	1.3	0.007	0.097	0.064
Ryegrass	19.2	7.6	21.4	5.0	3.6	2.5			
Sorghum Sudan	17.8	6.8	26.1	3.5	2.6	2.2			
Soybean	20.1	4.5	11.2	8.9	4.0	2.2	0.009	0.103	0.034
Timothy	10.7	4.5	17.0	3.2	1.1	0.9	0.005	0.055	0.036
Fruits and vegetables									
Apples	1.3	0.4	1.9	0.3	0.2	0.4	0.001	0.001	0.001
Bean, dry	41.7	13.9	13.9	1.1	1.1	2.8	0.011	0.017	0.033
Bell peppers	6.8	2.6	10.8		2.1				
Cabbage	2.9	0.8	2.9	0.4	0.2	1.0	0.001	0.002	0.002
Onions	2.7	1.2	2.4	0.7	0.1	1.1	0.002	0.005	0.018
Peaches	1.2	0.7	2.3	0.1	0.3	0.1			0.000
Peas	58.6	12.5	37.5	10.0	6.4	3.6			
Potatoes (white, vine)	3.0	1.6	5.3	0.2	0.2	0.2	0.002	0.005	0.003
Potatoes (sweet, vine)	2.4	1.1	5.8	0.2	0.2	0.4	0.001	0.004	0.002
Snap beans	15.4	3.7	18.2		1.9				
Spinach	4.5	1.3	2.7	1.1	0.4	0.4	0.002	0.009	0.009
Sweet corn	13.9	4.7	13.5		2.0	1.1			
Tomatoes	2.7	0.9	3.6	0.2	0.2	0.3	0.002	0.003	0.004
Turnips	20.1	8.9	40.2	5.4	2.7				
Other crops									
Cotton (seed & lint)	24.2	9.6	11.9	1.5	2.7	1.9	0.069	0.127	0.369
Cotton (trash)	19.0	5.3	24.0	18.7	5.3	5.0	0.017	0.020	0.250
Peanuts (nuts)	35.0	5.5	8.8	1.5	1.3	2.5	0.010	0.075	0.063
Peanuts (vines)	20.0	3.4	30.0	17.6	4.0	2.2	0.024	0.030	
Soybeans	95.6	20.8	37.6	9.7	5.1	11.7	0.025	0.031	0.025
Soybeans (crop residue)	14.6	2.6	12.1	4.9	1.5	2.0			
Tobacco, flue-cured (leaves)	28.3	5.0	51.7	25.0	5.0	4.0	0.010	0.183	0.023
Tobacco, flue-cured (stalks)	11.4	3.1	28.3		2.5	1.9			
Tobacco, burley (leaves)	36.3	3.5	37.5		4.5	6.0			

Source: Adapted from Zulbrina, 1991 (updated 1997).

TABLE 29
Total uptake of major nutrients by crops

Group/crop (main produce)	Total uptake of main produce					
	N	P ₂ O ₅	K ₂ O	S	Ca	Mg
(kg/tonne)						
Cereals						
Rice (paddy)	20.0	11.0	30.0	3.0	7.0	3.0
Wheat (grain)	25.0	9.0	33.0	4.7	5.3	4.7
Maize (grain)	29.9	13.5	32.8			
Sorghum (grain)	16.4	7.7	25.5			
Pearl millet (grain)	31.8	17.4	61.3			
Finger millet (grain)	24.2	9.5	30.6			
Pulses						
Chickpea (grain)	60.7	9.2	39.2	8.7	18.7	7.3
Pigeon pea (grain)	70.8	15.3	16.0	7.5	19.2	12.5
Lentil (grain)	57.0	14.9	21.6	3.0	7.5	2.0
Green gram (grain)	106.0	48.1	73.2	12.0	71.0	43.0
Black gram (grain)	78.9	14.4	65.6	5.6		
Oilseeds						
Groundnut (seed)	58.1	19.6	30.1	7.9	20.5	13.3
Brown mustard (seed)	64.5	20.6	53.4	16.0	56.5	9.5
Rocket salad (seed)	70.0	26.0	61.1	20.7	19.3	9.3
Soybean (seed)	70.7	30.9	57.7	6.7	14.0	7.6
Safflower (seed)	38.8	8.4	22.0	12.6		
Sesame (seed)	51.7	22.9	64.0	11.7	37.5	15.8
Sunflower (seed)	63.3	19.1	126.0	11.7	68.3	26.7
Linseed (seed)	60.0	18.6	54.0	5.6	31.2	13.1
Castor (seed)	40.0	9.0	16.0			
Tubers						
Potato (tuber)	3.3	0.9	6.2	0.4	1.0	1.8
Cassava (tuber)	5.0	2.3	6.8	0.4	2.7	1.0
Sugar crops						
Sugar cane (cane)	2.1	1.2	3.4	0.3		
Fibres						
Cotton (seed cotton)	43.2	29.3	53.3			
Jute (dry fibre)	35.2	20.3	63.2		39.7	8.0
Fruits						
Mango (fruit)	6.7	1.7	6.7			
Banana (fruit)	5.6	1.3	20.3			
Citrus (fruit)	9.0	2.0	11.7			
Apple (fruit)	3.3	1.5	6.0			
Guava (fruit)	6.0	2.5	7.5			
Pineapple (fruit)	1.8	0.5	6.2			
Sapota (fruit)	1.6	0.6	2.1			
Papaya (fruit)	2.8	0.8	2.2			
Grapes (fruit)	3.9	0.6	6.2			
Zyziphus (fruit)	4.0	1.8	6.3			

Continued

Blank spaces indicate data not available.

Source: Published Indian data summarized in Tandon, 2004.

TABLE 29
Total uptake of major nutrients by crops (continued)

Group/crop (main produce)	Total uptake of main produce					
	N	P ₂ O ₅	K ₂ O	S	Ca	Mg
Vegetables						
Tomato (fruit)	2.8	1.3	3.8			
Cauliflower (curd)	4.0	2.0	4.0			
Cabbage (head)	3.5	1.3	4.2			
Beet root (root)	4.4	2.0	6.7			
Carrot (root)	3.9	1.7	6.6			
Onion (root)	2.7	1.3	3.9			
Plantations						
Coconut (1 000 nuts)	8.1	3.9	12.1	0.0	4.9	1.8
Oil-palm (fruit bunches)	3.7	1.0	4.4			
Cocoa (dry beans)	22.7	10.2	53.3			
Tea (marketable)	178.3	3.5	115.1	10.0	41.7	11.5
Coffee (green beans)	129.0	27.0	174.0	5.0		
Rubber (latex)	30.0	9.0	72.0			
Cashew (nuts)	88.0	25.0	42.0			
Cardamom (dry capsules)	260.0	40.0	520.0			
Forages						
Hybrid Napier (dm ¹)	8.5	5.1	17.8	1.9	4.7	2.8
Grasses*						
Mean of 7 crops (dm ¹)	9.4	3.4	17.0	2.0	4.6	2.7
Medicinal						
Japanese mint (dm ¹)	12.9	7.5	18.5			
Aromatic plants						
Pyrethrum (dm ¹)	15.0	12.0	84.0			

¹ dm = dry matter.

Blank spaces indicate data not available.

Source: Published Indian data summarized in Tandon, 2004.

can differ owing to the differences among crops, genetic character of a variety, environment where they grow, fertility level of the field, yield level, luxury consumption, nutrient imbalances and post-absorption events such as lodging and leaf fall. Thus, in order to produce 1 tonne of grain, the uptake by a given crop can vary 1.7-fold in the case of N, 2.3-fold in the case of P and 3.6-fold in the case of K among locations (Tandon, 2004).

Fate of nutrients absorbed by crops

The nutrients taken up by a crop are distributed in different parts of the plant during its life span. In the case of grain crops, 70–75 percent of N and P, 25–30 percent of K and 40–60 percent of S absorbed ends up in the grain, the rest stays in straw/stover. In rice, more than 70 percent of the N absorbed is transferred to the grain while a greater proportion of K, Ca, Mg, Fe, Mn and B remains in the straw. The absorbed S, Zn and Cu are distributed about equally in grain and straw (Yoshida, 1981). In groundnut, out of the nutrients absorbed, the kernels contain

TABLE 30
Average uptake of micronutrients by crops

Crop	Economic yield ¹ (tonnes/ha)	Total uptake (g)					
		Zn	Fe	Mn	Cu	B	Mo
Rice	1.0	40	153	675	18	15	2
Wheat	1.0	56	624	70	24	48	2
Maize	1.0	130	1 200	320	130	-	-
Sorghum	1.0	72	720	54	6	54	2
Pearl millet	1.0	40	170	20	8	-	-
Cassava	1.0	45	120	45	5	15	-
Potato	1.0	9	160	12	12	50	< 1
Chickpea	1.5	57	1 302	105	17	-	-
Pigeon pea	1.2	38	1 440	128	31	-	-
Soybean	2.5	192	866	208	74	-	-
Groundnut	1.9	208	4 340	176	68	-	-
Mustard	1.5	150	1 684	143	25	-	-
Sunflower	0.6	28	645	109	23	-	-
Sesamum	1.2	202	952	138	140	-	-
Linseed	1.6	73	1 062	283	48	-	-
Jute (olitorious)	1.0	214	784	251	27	-	-
Jute (capsularis)	1.0	139	368	119	18	-	-
Coffee (arabica)	1.0	35	83	62	82	-	-
Tea	1.0	276	2 007	1 933	632	101	-
Guinea grass	269.0	558	2 940	1 880	443	-	-
Bersem	112.0	980	650	580	95	-	-

¹ Data for crops 1–7 are on per tonne yield basis; rest for indicated yield levels.

Source: Published Indian data summarized in Tandon, 2004.

41 percent of N, 52 percent of P, 28 percent of K, 11 percent of Mg and 1 percent of Ca. The leaves and stalks contain 45–50 percent of total NPK absorbed and also the bulk of Ca and Mg (Kanwar, 1983). In potato, harvested tubers account for 80, 83–88 and 70–78 percent of total N, P and K absorbed, respectively. In cassava, the proportion of absorbed nutrients present in tubers is 23 percent of N, 32 percent of P, 38 percent of K, 12 percent of S, 11 percent of Ca and 29 percent of Mg (Howeler, 1978). In jute, the proportion of absorbed nutrients that is returned to the soil before harvest through leaf fall is particularly high.

In tea, 50–65 percent of the N, P, K and Mg absorbed are removed from the field. The figure is about 35 percent for Ca, 25 percent for Mn and 25–50 percent for all the others. In coffee, the nutrient removal follows the order: K > N > P > Ca > Mg > S. The beans take away one-third of the nutrients that the plant absorbs and the remaining amount is retained in the plant biomass. Significant differences in nutrient uptake are observed between the arabica and robusta varieties of coffee. In coconut, the bulk of the nutrients absorbed ends up in nuts, leaves and stipules. Nuts alone account for 51 percent of N, 50 percent of P, 78 percent of K, 23 percent of Ca and 41 percent of Mg absorbed by the cultivar West Coast Tall (Pillai and Davis, 1963). In rubber, 25 percent of the N, 33 percent of the P₂O₅ and 8 percent of the K₂O absorbed is removed through latex. A considerable

proportion of the absorbed nutrients is returned back to the soil through leaf litter. In cardamom, less than 10 percent of nutrients absorbed are carried in the capsules. In tree crops, considerable amounts of absorbed nutrients are retained in the trunk and branches. For practical purposes, these can be considered as nutrients removed from the soil.

These and similar data underscore the point that nutrient removals cannot be equated with nutrient uptake, as is very often done particularly for estimating nutrient removals and calculating balance sheets. Although the final economic produce contains only a part of what the crop absorbs, it is the total need of the crop that has to be met by the soil and through external additions for optimizing plant nutrition.

Where crop residues are left on the field, the nutrient content of residues (although a part of uptake) does not constitute removal. Where crop residues are removed, they may be lost forever or returned back in the form of animal dung/FYM where they are used to feed farm animals. The very heavy losses through erosion highlight the need for large-scale measures in soil and water conservation in order to reduce the depletion of soil nutrients. However, in many cases, these could be intersite nutrient transfers.

Crop recovery of added nutrients and their implications

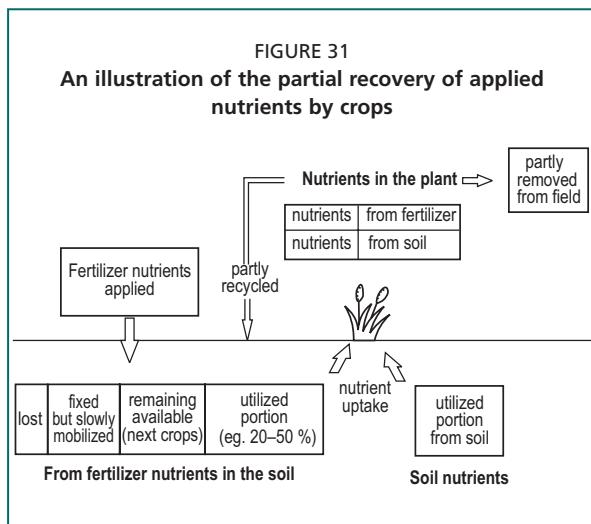
The amounts of nutrients added through fertilizers and other sources are only partly utilized by the crop (Figure 31). There are four possibilities for what may happen to the added nutrients:

- They enter the pool of available forms and are absorbed by the fertilized plants (recovered portion).
- They are not absorbed but remain available and are partly utilized by the next crop (residual).

- They are “fixed” and thus removed from nutrient cycling for longer periods.
- They are lost from the soil (through ammonia volatilization, leaching, and denitrification in the case of N).

The recovery or utilization rate of an applied nutrient is the portion of the added nutrient that is taken up by the plants. It is expressed as a percentage of the nutrient amount supplied. A recovery of 50 percent means that half of the fertilizer nutrients applied has been utilized by the fertilized crop. The recovery rate for applied

FIGURE 31
An illustration of the partial recovery of applied nutrients by crops



Source: Finck, 2006.

nutrient is often high for K (up to 70 percent), medium for N (35–70 percent), comparatively low for P and S (15–30 percent), and very low (less than 10 percent) for micronutrients.

The nutrient recovery rate is an important indicator of the fertilizer-use efficiency although it may at times include luxury consumption. Existing data on the subject are variable because recovery is affected by the soil, crop growth, root characteristics and production conditions. Nutrient recovery data are approximations with inherent variations. Moreover, the recovery rate of applied nutrients may be seen with reference to different time intervals, such as a specific growth period of a crop, single-crop basis, crop-rotation basis or for several years, as in case of P and some micronutrients. The recovery rate also depends on the extent to which the soil is supplied with nutrients, i.e. whether the soil is deficient or well supplied. Moreover, true recovery must be distinguished from apparent recovery.

The two methods for determining the recovery rate of applied nutrients are:

➤ Difference method (indirect measurement): The difference between nutrient uptake from fertilized (total uptake) and unfertilized plots is measured as in a fertilization experiment and related to the fertilizer quantities applied. The utilization or recovery rate is then given by the formula:

$$\text{Recovery rate (in \%)} = \frac{\text{total uptake} - \text{uptake from soil} \times 100}{\text{nutrient amount added in fertilizer}}$$

Example for N (amounts in kg/ha):

N added through fertilizer = 120 kg N

Total uptake from fertilized soil = 100 kg N

Uptake from soil (without fertilization) = 40 kg

Recovery rate of applied N = $100 - 40 = 60 / 120 = 0.5 \times 100 = 50$ percent.

➤ Isotopic method (direct measurement): It also requires the conduct of an experiment, but the recovery is determined only on one plot by labelling the fertilizer nutrient with isotopes in order to distinguish fertilizer nutrients from soil nutrients. (For phosphate, the specific activity is the ratio of $^{32}\text{P}/^{31}\text{P}$ isotopes.)

The utilization rate is derived in three steps (e.g. for phosphate per hectare):

$$1) \text{ percent fertilizer P in plants} = \frac{\text{specific P activity in plants} \times 100}{\text{specific activity in fertilizer}}$$

$$2) \text{ kg fertilizer P in plants} = \frac{\text{kg P in plants} \times \% \text{ fertilizer P in plants}}{100}$$

$$3) \text{ utilization rate (in \%)} = \frac{\text{kg fertilizer P in plants} \times 100}{\text{kg fertilizer P added}}$$

The isotopic method is based on the assumption that fertilization does not affect the uptake of nutrients from the soil. However, this may not be completely correct. The fraction of nutrients absorbed from the soil may be reduced by fertilization in many cases and increased in other cases because of the so-called “priming effect”,

TABLE 31
Average utilization rate of fertilizer nutrients by the first crop

Nutrient and source	Utilization rate (% recovery)
Nitrogen, mineral	50–70
Nitrogen, slurry	30–50
Nitrogen, manure	20–40
Phosphate, mineral	10–20
Potassium, mineral	50–60
Micronutrients, mineral	0.5–5

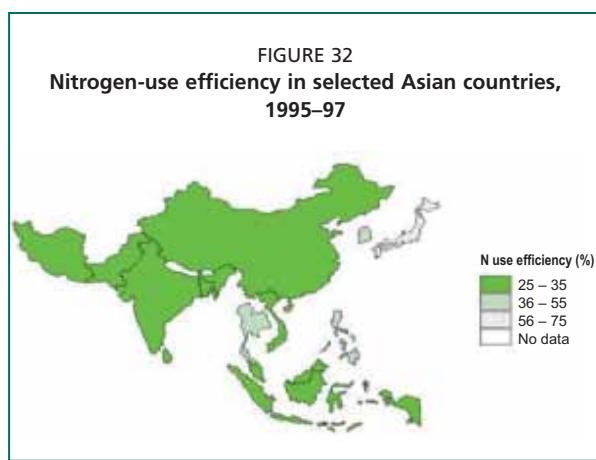
deficiencies by changing root growth and their capacity to absorb nutrients. The recovery estimates using tracers (isotopes) may be affected by internal cycling of nutrients in the soil, such as the mineralization–immobilization turnover in the case of N (Bruulsema, Fixen and Snyder, 2004).

Table 31 presents some average ranges of the recovery of applied nutrients by crops (based mainly on cereals but including some other crops as well). It is possible to achieve even higher values in greenhouse trials, but recovery rates of up to 80 percent are rarely obtainable in soils. The utilization rate can often be increased by careful fertilizer placement, but only on deficient soils. In the first year with intensive cropping, the utilization rates for mineral N fertilizers can be 50–70 percent, e.g. for cereals grown under good conditions. However, recovery of applied N for paddy rice is estimated to range from less than 30 up to 70 percent in Asia (1995–97). (Figure 32).

An understanding of the relationships between crop yields, N use and N recovery can provide important clues to close the existing rice yield gaps. A categorization of selected Asian countries based on rice yield, N use and N recovery presents an interesting picture (Table 32). Most countries, with the exception of the Republic of Korea, Japan and China, fall within the medium- and low-yield groups, indicating considerable scope for raising yields. Although the level of N use in the Republic of Korea (178 kg/ha) is double that of Japan (88 kg/ha), the yield difference is small (0.2 tonnes/ha) as a result of the efficiency factor (recovery). Enhanced nitrogen-use efficiency (recovery of applied N) in the Republic of Korea may lead to optimized N use while maintaining yield levels similar to those in Japan. For countries such as China,

so that the method may indicate a higher or lower value than the actual value. To date, no method has been developed to establish “true” values for the recovery of applied nutrients by crops.

Both the difference method and the method using isotopes can be subject to errors. Errors may arise in the difference method because plants respond to nutrient



Source: FAO, 2003c.

Indonesia and the Islamic Republic of Iran, improved nitrogen-use efficiency accompanied by optimization of nitrogen-use levels would be a suitable approach for closing the yield gap. The possibilities for raising yields in Viet Nam, Sri Lanka, Malaysia, India and Pakistan remain high, provided that the prevailing low N recovery rates can be improved. The enhancement of N use to medium levels, coupled with efficiency improvement measures, is important for the Philippines, Bangladesh and Thailand (FAO, 2003c).

Among organic sources, the recovery rate of N provided through leguminous green manure

can be much higher than the N input from FYM or compost. Part of the unused residual N remains in the soil and can be used for the next crop, and part of it may be lost. For the organic manure slurry applied on the soil surface, the utilization rate of N is about 30–50 percent but this can be improved by injecting it into the soil.

The utilization rate for P fertilizers in the first year can be up to 25 percent, especially with row placement for wide-row crops, but only 10 percent or less with PR applied under unfavourable soil conditions or with broadcast application. The utilization rate for P increases over the longer term as residual effects are considered. Where the utilization rate of fertilizer P is 15 percent in the first year, the residual effect in the second year is about 1–2 percent, and about 1 percent in the following years. Cumulative values for longer periods are: about 25 percent for 10 years; and about 45 percent for 30 years. For very long periods, the recovery may approach 100 percent. Most farmers are not willing to wait that long to adjust their nutrient application rates although it does result in a long-term buildup of the nutrient capital of the soil. With K fertilizers, the first-year utilization rate is about 50–60 percent but long-term rates are higher. The recovery rate of soil-applied micronutrients is extremely low, and for nutrients such as Cu and Zn, a single application can last for several crops.

The assessment of the recovery rate over very long periods is only meaningful with respect to the apparent utilization (discussed below). Fertilizer utilization on well-supplied soils is generally lower than on deficient soils, at least in the first year. This is because the soil already contains sufficient nutrients for the plants, and fertilization serves primarily to replenish reserves.

TABLE 32
Categorization of selected countries based on rice yield, nitrogen use and nitrogen-use efficiency, 1995–97

Country	Yield level ^a	Nitrogen use ^b	Nitrogen-use efficiency ^c
Republic of Korea	H	H	M
Japan	H	M	H
China	H	H	L
Indonesia	M	H	L
Iran	M	H	L
Viet Nam	M	M	L
Sri Lanka	L	M	L
Malaysia	L	M	L
Philippines	L	L	M
India	L	M	L
Pakistan	L	M	L
Bangladesh	L	L	L
Thailand	L	L	M

^a Yield: H (high) = 5.5 tonnes/ha and higher; M (medium) = 3.6–5.5 tonnes/ha; L (low) = 3.5 tonnes/ha and lower.

^b N use: H (high) = 120 kg/ha and higher; M (medium) = 81–20 kg/ha; L (low) = 80 kg/ha and lower.

^c Nitrogen-use efficiency: H (high) = 55% and higher; M (medium) = 36–55%; L (low) = 35% and lower.

Fertilizer amounts required according to nutrient removal and recovery

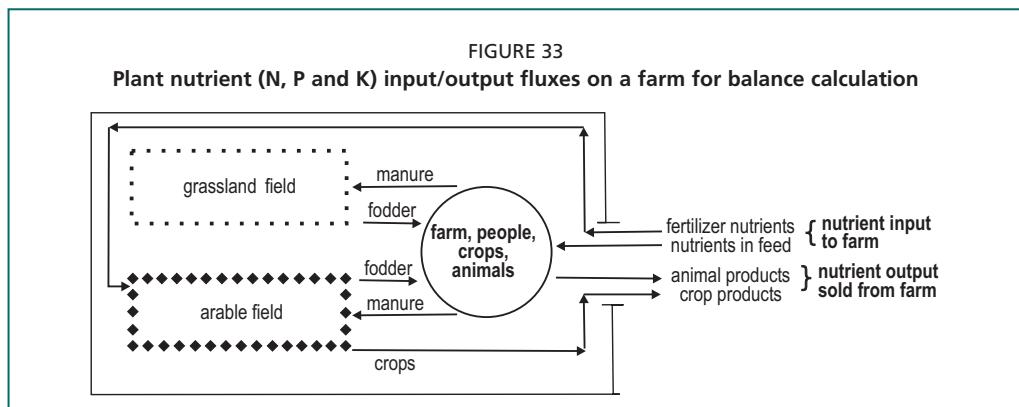
Optimal fertilization should be based on crop removal data in the case of nutrients such as N for which reliable soil test methods are not available. There should be a provision to deduct for luxury consumption from the nutrient removal data, and the effort should be to strive for high recovery of added nutrients. Luxury consumption is particularly relevant for N and K but less so for P, S, Mg, etc. The best way to optimize the application of nutrients that leave a substantial residual effect is to manage them on a crop-rotation basis. Fertilization on the basis of micronutrient removal is not advisable on deficient soils because of their very low utilization rate. Application of these nutrients should be based on available nutrient status of the soil and the period over which a single application can leave significant residual effects (so that micronutrient applications are not repeated each year). For nutrients for which soil application is not very effective (e.g. Fe and Mn), the amounts required can be calculated for foliar applications or in terms of chelates.

Nutrient accounting via input/output balances

Sustainable cropping should not exhaust the soil nutrient supply but improve it to the extent possible. The extent to which this advice is followed depends on the farmer's perception of sustainability and available resources for purchasing fertilizers. This is also an area where INM can play a role by enabling the farmer to recycle all available on-farm and off-farm organic wastes.

A quantitative knowledge of the depletion of plant nutrients from soils may be helpful in devising nutrient management strategies. Nutrient balance exercises serve as instruments to provide indicators for the sustainability of agricultural systems. Nutrient budget and nutrient balance methodologies using various approaches for different situations have been applied widely in recent years at a variety of levels: plot, farm, regional, national and continental (FAO, 2003b).

In agriculturally advanced countries, a farmer can check whether the input by fertilization corresponds to the nutrient removal in order to maintain soil fertility. At the farm level, the amounts of nutrients leaving the farmgate can be used as a criterion for adequate nutrient management. The input of both plant nutrient sources and plant nutrients in animal feed must correspond to the nutrient removal by the crop and in exported animal products. Figure 33 shows the input/output fluxes of plant nutrients (N, P and K) on a farm measured at the farmgate for balance calculation purposes. In this case, the nutrient losses and BNF are not shown. A farmer can carry out such calculations with the aid of standard tables containing nutrient concentrations of fertilizers and feedstuff. Such a calculation also provides information about unaccounted losses, which is required by some fertilizer laws in view of environmental pollution. The problem with this calculation is that unaccounted differences may not only be caused by losses but also by enrichment of soil fertility. Such exercises can be conducted by educated, well-informed farmers who maintain an accurate bookkeeping of various inputs and outputs. Even then, they can benefit from consulting their local farm adviser or extension specialist.



Source: Finck, 2006.

This type of exercise may not be possible for the vast majority of smallholders in most developing countries. In most such cases, farmers have access only to general fertilizer recommendations, supplemented by whatever quantities of organic manures are available in their village. To minimize the depletion of soil fertility, they can base nutrient application rates on soil test results wherever these are available. The farmers can also be encouraged to recycle as much crop residue as possible and, instead of using cattle dung as a source of domestic fuel, recycle it through biogas plants in order to obtain energy as well as manure.

At the regional or national level, an input/output balance of plant nutrients can reveal significant nutrient losses with the sale or export of agricultural products that are not compensated by external nutrient additions. This is a kind of interregional nutrient transfer in which the importing area is enriched with nutrients and the exporting area can be depleted of nutrients (mining of soil nutrients) by exhaustive cropping. While calculating nutrient balances, several nutrient-specific features may be observed. Some possible explanations for these are:

- Nitrogen: Where the N input is much greater than the N output, this indicates a low level of nitrogen-use efficiency, which could be either the result of large losses or of small losses combined with enrichment of soil N reserves. Where the output exceeds the input, there must be a substantial gain from BNF or from depletion of soil N reserves.
- Phosphorus: In intensive cropping, the optimal input of P is usually greater than the P output owing to low P-use efficiency as a result of the enrichment of mineral and organic soil P fractions. This should be considered as a positive long-term effect. This enrichment or buildup of P can contribute to the P nutrition of several crops in succession. This has implications also for the economics of P application (Chapter 9).
- Potassium: The K balance depends largely on the rate of N and K application, any luxury consumption of K, utilization of soil K reserves (particularly from the non-exchangeable fraction) and K losses. K losses are a possibility in coarse-textured soils under high rainfall.

- Calcium, magnesium and sulphur: The Mg balance is similar to that of K, except in neutral and alkaline soils where Mg may be abundant. The Ca balance is generally of little interest. The S balance tends to be negative if the addition of sulphate from the atmosphere or irrigation water is not included, or S-free fertilizers are used particularly for high S-demanding crops, such as oilseeds and fodders.
- Micronutrients: Balancing micronutrients makes little sense because their availability is of major importance (not any input/output calculation). In any case, under most situations, nutrient balances for micronutrients are positive owing to the low use efficiency of applied nutrients by crops (similar to P).

STRATEGIES FOR OPTIMIZING NUTRIENT MANAGEMENT

Nutrient management can be considered from different aspects, such as with the emphasis on soil nutrient status, on crop productivity, on nutrient balances or in terms of the nutrient–water relations.

The ultimate aim of all aspects is to: optimize crop production, maximize positive interactions, maximize net returns, minimize the depletion of soil nutrients, and minimize nutrient losses or negative impact on the environment. Achieving this aim is difficult but not impossible. It requires the application of best available knowledge and inputs as part of a medium- to long-term strategy. For most situations, the required knowledge and inputs are already available. The key is the intelligent management of the various resources.

From soil nutrient exploitation to enrichment

Different strategies of soil nutrient management in cropping systems have evolved over time. These are related to different systems of fertilization. Different strategies may find application simultaneously in the same region, and sometimes on the same farm, and thus be largely responsible for differences in fertilizer input per unit area. The four different strategies concerning soil nutrients are:

- exploitation: exhaustion of soil reserves, no fertilization, decreasing yields;
- utilization: moderate withdrawals from soil reserves, no fertilization, stable yields;
- replacement: maintenance of soil supplies, fertilization to offset removals, stable yields;
- enrichment: enhancement of soil supplies, supplementary fertilization, increasing (high) yields.

Exploitation of soil nutrients

Cropping based on the exploitation (unwise utilization) of nutrients stored in the soil is the oldest strategy of agricultural production. Exploitation cropping uses the natural nutrient capital of the soil. It still plays an important role in crop production in many regions. A common feature of all exploitation systems is that hardly any fertilization or nutrient replenishment is undertaken apart from

recycling harvested residues and waste products. This results in nutrient depletion through mining the soil reserves. As a result, the yields decrease from year to year. The available nutrients are consumed until they are exhausted, either because the mobilization rate of organic and mineral reserves is very low or there are only small soil nutrient reserves left to be mobilized. The original fertility of the soil, which had improved over long periods, is thus depleted.

Typical examples of rapidly decreasing soil fertility are found with shifting cultivation in humid forest areas. On newly developed lands with high soil fertility, soil nutrient exploitation may permit highly profitable cropping for several years without fertilizer input. Even outside shifting cultivation, a large number of farmers in many developing countries continue to raise crops drawing primarily on soil nutrient reserves.

Despite all the objections to exploitation cropping as such, controlled exploitation cropping may be useful economically and may even be ecologically acceptable as a stable form of land use, provided that the arable cropping period is limited and that a fallow period is included for regeneration of soil fertility. This may not always be possible in intensively farmed, overpopulated countries, particularly where irrigation or adequate rainfall is available to raise an additional crop. It is a feature of subsistence agriculture in which very little marketable surplus is generated.

Long-term exploitation cropping can cause considerable damage to soil fertility as serious soil degradation may occur. Such serious damage is not completely irreparable, but the cost of regeneration exceeds the short-term gain achieved. Exploitation cropping accompanied by irreparable damage represents destruction of a naturally available potential that humanity, with its continuously shrinking living space, cannot afford. Such an approach is not sustainable for improving crop yields.

Utilization of soil nutrients

This is a less severe version of the exploitation (mining) of soil nutrient reserves discussed above. Similar to exploitation, utilization of soil nutrients involves a certain reduction in the nutrient capital of the soil without a significant decline in the fertility taking place. This may create the impression of a sustainable system of agricultural production without external nutrient input. Such nutrient supply systems can only be practised where the nutrient removals are small and the pool of available nutrients is large and also backed by sufficient a rate of nutrient mobilization from the soil reserves.

In this system, the soil is not impoverished significantly and yields remain constant in spite of annual nutrient removal. However, the fact that yields remain low in such a system makes it unsuitable whenever the farmer wants to improve his yield levels. Then, this strategy will come closer to the exploitation strategy and will have to be replaced by a more balanced output/input regime. No soil, even the most fertile one, can continue to support nutrient removals indefinitely. Again, this system is not sustainable for producing high yields.

Replacement of soil nutrients

The concept of replacing nutrients that are removed or lost from the field permits stable cropping and was practised in ancient civilizations. Examples of this are the natural replacement of nutrients by Nile mud in Egypt, regular use of animal dung as manure in ancient India, and careful compost management in ancient China. Today, especially on most soils with only average fertility, the replacement of all losses is essential for sustaining optimal levels of crop productivity with minimum depletion of the soil reserves.

Maintenance of soil fertility can be partly achieved by using soil-improving crop management practices. These include using nutrient-accumulating plants such as legumes for the accumulation of N or by following crop rotations with different nutrient demands and different rooting depths. Both organic and mineral nutrient sources are suitable for the replacement of soil nutrients. Farm waste products and mineral sources such as silt and marl can also be used as supplements to fertilizers for obtaining moderate to high yields.

The strategy of nutrient replacement is valid only in cases of good initial soil fertility or soils in which the fertility has been built up to an adequate level through repeated fertilization. It is not applicable on naturally poor or depleted soils because fertilization on the basis of removals only can further deplete such soils. The root cause of soil fertility depletion here is that only a part of the nutrients absorbed by the crop are provided by external input and the remaining crop needs are met from soil reserves.

Cropping systems based on the replacement strategy are only rarely used to the full extent. They are very common in a modified form in which the replacement of some nutrients (especially N, P and K) occurs but others are utilized from the soil reserves. This is most common where balanced nutrient application is restricted to the narrow meaning of NPK application. This strategy can allow yields to be kept at medium or even at high levels as long as nutrients other than N, P and K are not limiting.

Enrichment of soil nutrients

Natural soil fertility is often insufficient for sustaining high yields and may further decline after a few years of intensive cropping. Because of this, the level of some nutrients must be increased beyond the amounts needed to replace the removals in order to achieve high yields. Enrichment of soils with nutrients should primarily extend to those nutrients that can be built up and not necessarily to all nutrients. This strategy comprises three approaches: (i) increasing the supply of deficient nutrients beyond the amounts removed; (ii) replacement of removals in the case of nutrients present in sufficient amounts; and (iii) utilization of nutrients from soils endowed with good reserves and nutrient replenishment capacity.

Improvement in soil fertility by nutrient enrichment manifests itself historically by the fact that, in parts of Europe, sugar beet and wheat now produce high yields on soils formerly considered as far too poor for these nutrient-demanding crops. Better nutrient supply over the years and the resulting improvement in

soil fertility in general has raised the yield potential of these crops substantially to an upper limit imposed only by climate or other limiting factors that are difficult to correct. Enrichment of the relevant nutrients can be very profitable because of the much higher yield level achieved, provided economic resources are not a constraint.

The strategy of fertilizing for soil fertility buildup is practised, for example, by farmers in the advanced maize production state of Illinois in the United States of America. Based on the available P status of the soil, phosphate application is recommended with the twin objectives of building up soil available P to an optimal level and replacing P removals by the crop at expected yield levels (Table 33). Once the available soil P status has reached the optimal level, only replacement of P removal is recommended (University of Illinois, 1994). This is a case study of an approach for sustaining high yields.

The concept of enrichment of the limiting nutrients does not mean a perpetual increase in the soil P status, but only an increase up to an optimal supply level that is sufficient for high yields, and certainly not up to luxury supply, which would be both unnecessary and detrimental in view of nutrient losses and imbalances. The enrichment phase is usually a transient one that is followed by a permanent replacement phase, generally at a high yield level. A large number of farmers in many developing countries may not be able to adopt this approach primarily owing to inadequate financial resources, high cost of purchased inputs, and a lack of perception concerning the need for enriching soil nutrient reserves. Many such farmers operate on a season-to-season or at most on a crop-rotation basis. Their weak financial base forces them to look for short-term gains.

INTEGRATED NUTRIENT-WATER MANAGEMENT FOR OPTIMIZING PLANT NUTRITION

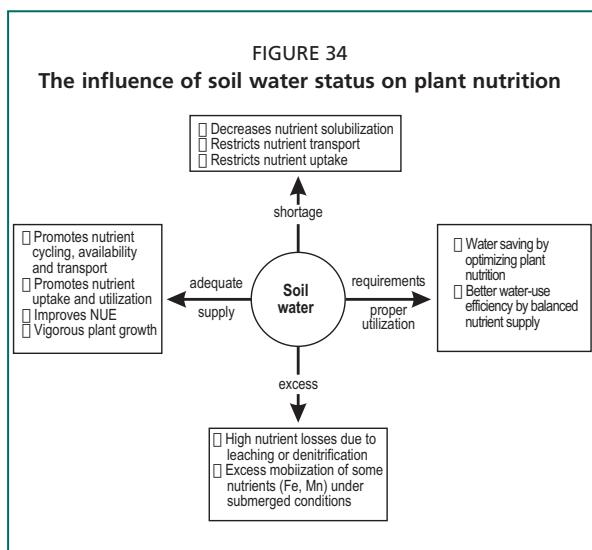
Plant needs for water and nutrients are interdependent. Water is not only required for the growth of plants but is also the medium through which nutrients are transported to the roots and absorbed by them. A good water supply improves the nutritional status of crops, and an adequate nutrient supply saves water. With properly coordinated management of nutrients and water, the farmer can increase crop productivity substantially through their efficient use. This holds true both for irrigated and rainfed situations. Application of optimal nutrients without access to adequate water results in poor utilization of the applied nutrients. Similarly, application of low doses of nutrients under conditions of adequate

TABLE 33
Buildup and maintenance approach for making fertilizer recommendations for maize¹

Bray and Kurtz P ₁ – test (mg P/kg soil)	P ₂ O ₅ recommended		
	For buildup to optimum	For replacing crop removal	Total P ₂ O ₅
4	92	64	156
8	83	64	147
16	65	64	129
24	47	64	111
32	29	64	93
40	11	64	75
45	0	64	64

¹At a grain yield level of 9 400 kg/ha on a soil with medium P-supplying power in Illinois, the United States of America

Source: University of Illinois, 1994.



Source: Finck, 2006.

water supply results in a waste of the valuable water resource. Water management is inseparable from good nutrient management practices and vice versa.

Influence of soil water on crop nutrition

Soil moisture conditions have major effects on productive processes such as the accessibility, availability, uptake and use of soil nutrients for crop growth and also on negative processes such as creating anaerobic conditions, and losses of nutrients from the soil (Figure 34).

Water supply

The content of available soil water has a marked influence on several aspects of nutrient supply. Every soil has a certain WHC. This is the upper limit of available water and depends on profile depth, soil texture and soil organic matter content. Irrigation/rainfall above WHC is a waste as excess water is lost by runoff or drainage. Available water lies between field capacity and the wilting point. As adequate (but not excess) soil moisture results in profuse and deeper root growth, both water and nutrients become accessible to plants from deeper soil layers where moisture is adequate.

Where dry conditions restrict water uptake, e.g. during drought, the rate of root extension is reduced in soils of low fertility and the plant is unable to access deeper moist horizons in the soil. In most soils, the nutrient content is highest in the topsoil and this horizon dries out first. Although the plant is able to absorb some water from the subsoil, this may not be sufficient to obtain adequate nutrients for active growth. Phosphate plays a key role in the growth and proliferation of the root system. Where the soil is well supplied with phosphates before planting, the plant can develop a vigorous and deep root system before the onset of mid-season drought. Even when the surface soil becomes dry, such roots are capable of absorbing water and nutrients from deeper layers. In such cases, phosphate application can be considered as an insurance against drought. It not only increases crop growth but also enables a more efficient use of stored soil water that would otherwise have been out of reach of poorly developed roots.

Water and nutrient availability

Soil moisture affects the solubility and, hence, availability of all nutrients. Biological activity in the soil is particularly restricted under conditions that are

too wet (owing to lack of oxygen) or too dry. Under very dry conditions, the breakdown of organic matter, and with it the mineralization of organic forms of N and other nutrients into plant available mineral forms, slows down. This may lead to a temporary shortage of N in the soil. Thus, in very dry periods, little accumulation of mineral N occurs. When the rains come, there can be a considerable flush of mineralization, providing available N and other nutrients for plant growth, provided the subsequent heavy rains (as received during the monsoons) do not leach the mineralized N beyond the rootzone.

The use of irrigation can minimize fluctuations in soil biological activity during crop growth. One of the significant effects of irrigation or moderate rainfall is to increase soil nutrient supply from organic sources. However, such increases are seldom sufficient to meet the additional demand for nutrients resulting from greater plant growth. Mineralization of other nutrients such as P and S also increases with adequate soil moisture.

The availability of mineral potassium (K^+) and other cations is also improved by a satisfactory soil moisture status. In dry soil conditions, the cations in general are more tightly bound to soil colloids, not easily exchangeable and, therefore, are less available, or rather less accessible, to plants. In addition, as the volume of soil solution is smaller, the amount of sparingly soluble nutrients, such as P, is reduced and plants are unable to absorb them in required quantities.

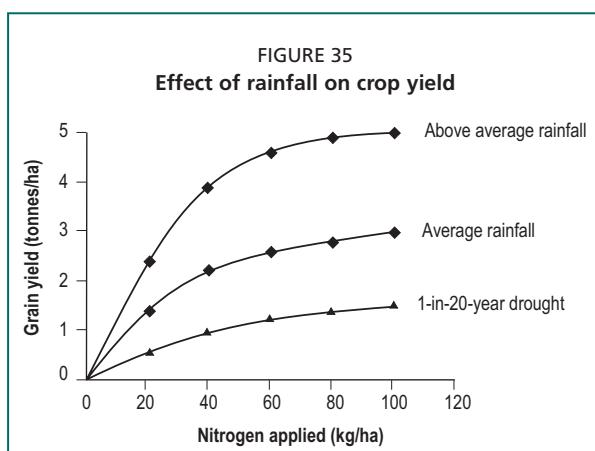
In waterlogged soils, the concentrations of ammonium ions, P, Fe and Mn increase, but the content of nitrate-N decreases because of leaching and denitrification. The uptake of many nutrients by rice such as N, P, Mn and Fe increases under waterlogged conditions but the uptake of other cations may be reduced. In this respect, the upland rice system is closer to most other cereals and quite different from the flooded-rice system.

Water and nutrient mobility

As nutrients need to move only a short distance, adequate soil moisture favours the mass flow of nutrients, especially N, with the soil solution to the root surface. Movement by diffusion within the soil solution is important for several nutrients including P and K and it is aided by adequate soil moisture. Moreover, the uptake of nutrients by crops is also enhanced where the plants have an adequate water status. Efficient use of nutrients within the plant for growth and metabolism also depends on a satisfactory uninterrupted supply of water. Where sufficient water is not available, transport of absorbed nutrients within the plant is restricted. This also restricts their use for metabolic activities and plant biomass production, which can ultimately have an adverse effect on the yield and nutrient content of the economic produce.

Water and crop response to nutrients

The growth and yield response of a crop to fertilizer application is very much influenced by the level of water supplied. Crop response is a synthesis of the various factors affecting crop growth, nutrient availability and nutrient uptake. The



Where plants have access to adequate water but not to adequate nutrients, this amounts to an underutilization of the valuable water resource.

Water and nutrient-use efficiency

In agronomic terms, NUE means the increase in yield obtained per unit of applied nutrient. It is the same as rate of response and can be calculated as: $\text{NUE} = (\text{yield of fertilized plot} - \text{yield of control plot}) / \text{amount of nutrient applied}$.

Many aspects of crop management influence the actual yield level and the response to applied nutrients. In relation to water supply and management, NUE may be improved by minimizing the fertilizer losses from the soil that are caused by poor water management, for example leaching or denitrification. The NUE can also be improved by ensuring that lack of water does not at any stage retard crop growth or nutrient uptake appreciably. Excess water can be a cause of nutrient losses, and insufficient water at a critical stage can limit growth and yield. It is also important that all other production inputs and management factors be adequate.

The timing of water application influences NUE considerably through its effect on crop yield, which can be reduced substantially where water supply through irrigation or otherwise is deficient at the most critical stages of crop growth. In most crops, the active vegetative growth stage and the reproductive growth stage have been found to be most critically affected by moisture deficiency as summarized below:

- rice: head development and flowering > vegetative period (active tillering) > ripening;
- wheat: flowering > yield formation > vegetative period (crown root initiation);
- sorghum: flowering and yield formation > vegetative period;
- maize: flowering > grain filling > vegetative period;
- peas: flowering and yield formation > vegetative period;

greater response to N, as well as a higher yield level, with increasing rainfall is shown in Figure 35. Such variations in rainfall greatly affect the optimal rate of nutrient application. For crops raised largely on stored soil moisture, an estimate of the moisture in the soil profile before planting is as valuable as an estimate of the available nutrient status of the soil. Consequently, more nutrient input is required to make use of a better water supply, and the economically optimal rate of nutrient application also rises.

- potato: stolonization and tuber initiation > yield formation > early vegetative growth;
- groundnut: flowering and yield formation, particularly pod setting;
- safflower: seed filling and flowering > vegetative period;
- cotton: flowering and boll formation;
- sugar cane: period of tillering and stem elongation > yield formation.

Water and nutrient losses

There are three main ways in which water status and water management can influence loss of nutrients from the soil–plant system.

Excessive rainfall, or excessive irrigation, resulting in the passage of water through the soil profile through deep percolation will carry with it soluble nutrients, particularly nitrate, sulphate and B. In temperate climates with moderate or high rainfall, the amount of rainfall during winter can cause appreciable loss by leaching of these nutrients. This is particularly the case where high amounts of such nutrients may be present in the soil at the beginning of winter (owing to breakdown of crop residues at the end of the growing season). The amount of loss depends on how much water moves through the soil profile and the stock of soluble nutrients. The extent of nutrient losses must be considered when determining nutrient application rates.

Leached nitrate can also enter water bodies or become denitrified under anaerobic conditions within the soil profile. Such conditions can exist within pockets or compact zones within an otherwise aerated soil. Waterlogging causes loss of N through denitrification of nitrate. In flooded-rice soils, nitrate levels can be kept low by placing ammonium or amide source of N, such as urea supergranules (USGs) in the reduced soil zone and by proper water management. However, in upland soils, nitrate levels are often quite high, such that periodic waterlogging by heavy rainfall as in a monsoon-type climate or excess irrigation can result in a large loss. As free-draining soils become waterlogged less readily, this risk is greatest on the high clay fine-textured soils.

Ammonia volatilization from urea and some ammonium-containing fertilizers is influenced by temperature, soil reaction and soil water status. Under very dry conditions, little loss occurs, and in stable wet soil conditions, ammonium remains in solution. However, where soil moisture status is intermediate, or where the soil or floodwater loses water rapidly by evaporation, volatilization of ammonia can be appreciable. This is particularly observed where urea is surface broadcast without incorporation on alkaline soils with inadequate moisture during periods of high temperature. Chapter 11 examines various routes of N loss from soils and the means to minimize them.

Crop nutrition influencing water demand

Water requirement of crops

Effective water management requires careful planning of crop production at farm level. Water requirement means the quantity of water needed for transpiration

from the green plants, evaporation from the soil and other water losses during application. Crops require 300–800 litres of water for transpiration in order to produce 1 kg dry matter. The amount of water consumed is both plant specific and climate dependent. It is also determined largely by the nutrient supply and the size of crop canopy or leaf surface. To minimize water requirements, various losses such as those during conveyance of irrigation water, runoff, seepage by deep percolation, leaching and waterlogging should be avoided. Water requirement (WR) must be met from water stored in the soil profile (Sw) plus rainfall (Rw) plus irrigation (Iw). Therefore, the irrigation water requirement (IR) = WR - (Sw + Rw). Even where the total amount of water is sufficient, this may not ensure high yields if there is a water deficit in critical growth stages (listed above).

Crop nutrition and water demand

A good nutrient supply also creates higher osmotic pressure in plant cells, which results in a better resistance to drought. Potassium ions (K^+) play an important role in regulating the functioning of stomata in the leaves that control water loss. Thus, a good supply of K can conserve water. Phosphate promotes early root growth, which allows better access to water from deeper soil layers and also shortens the growth period. This leads to early ripening, which reduces water demand. To a certain extent, a shortage of water can be compensated for by optimizing plant nutrition. Under low rainfall, nutrient input, especially of N, should be adjusted to the amount of stored soil water (Figure 36).

Water-use efficiency

As in the case of any production input, the efficient use of water is also of practical interest. Water use in crop production is not confined to transpiration from plants. Additional water losses such as evaporation must be considered in calculations of water-use efficiency (WUE). WUE is defined as the economic crop yield (Y) per unit of water used by the crop for evapotranspiration (ET). It is expressed in kilograms of crop per millimetre of water used:

$$WUE = \frac{Y}{ET} \text{ kg/mm}$$

In recent years, WUE has increased considerably owing to substantial yield increases as a result of improved nutrient supply, especially of N, P and K. As water supply is often a limiting factor in crop production and irrigation is both expensive and finite in quantity, any practice that increases yield per unit of water used is important. Good nutrient supply must complement irrigation or else part of the additional water will be wasted, leading to a drop in WUE. Once full crop cover is achieved, water use (ET) from the field is controlled mainly by incoming solar energy, nutritional status, etc. In these circumstances, any input factor that increases economic yield improves WUE.

Optimizing plant nutrition should aim to maximize both NUE and WUE. The best way to achieve this will depend on the soil fertility status, the water regime

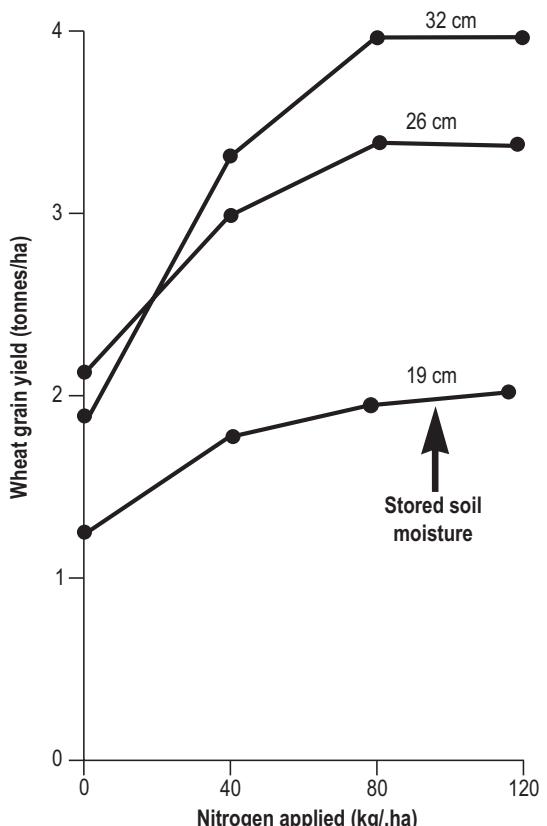
in a given production system, and moisture conservation practices such as mulching.

For rainfed dryland crops, the plants often have to face moisture stress at some stage of growth. Whatever the level of fertilizer used, the factor most often limiting production is water supply. Fertilizer rates must be decided in relation to the level of water supply from stored soil moisture and the anticipated rainfall, which determine the yield (Figure 36). It is advisable to apply N in more than one split in order to take advantage of rainfall expected during crop growth. Under very “dry” conditions, too much fertilizer applied before planting or very early on during crop growth may affect crop yield and WUE adversely by stimulating excessive vegetative growth, which uses up the limited water supplies leaving very little water for the reproductive and grain-filling stages of growth. This is a case where a luxuriant crop stand can be counterproductive.

For irrigated upland crops, the fertilizer requirement is normally high and the amount to be applied can be decided in relation to soil fertility level, expected yield and local management practices. Both NUE and WUE will be maximized by providing adequate amounts of both water and nutrient inputs for full growth and yield. Their applications should be timed so that crop nutrient and water needs are always met.

In wetland rice, provided water management is good, yields are determined by climate, season, variety, management and the nutrients applied. The amount of fertilizer, method of application and timing are all important. Generally, the NUE and WUE are lower in such systems compared with upland crops because of the large volume of water required and high N losses. The efficiency of both the inputs can be improved by applying N in 2–3 splits during crop growth and by using efficient N carriers. There is scope for economizing on water in flooded-

FIGURE 36
Response of rainfed wheat to nitrogen in soils with different stored moisture levels



Source: Meelu, 1976.

rice culture because, if the soil can be kept saturated, waterlogging or deep submergence may not be required.

PLANT NUTRITION AND RESISTANCE TO STRESS

A crop can suffer from several types of stresses during its growth. These may be caused by soil, moisture, temperature, salinity, nutrient deficiencies or toxicities, pests and diseases. The response of crops to various stresses is often affected by their nutrient status. Optimizing plant nutrition can enable the crop to withstand such stresses and emerge with minimum loss of yield. The role of some plant nutrients such as K in this regard has been investigated in considerable detail. The subject of plant nutrition and resistance to various climate and other stresses is discussed in brief here. Vlek and Vielhauer (1994) provide a detailed review of the subject with special reference to N, P and K.

Tolerance of plants to water stress

Water stress to varying degrees is often experienced by plants at some stage even under irrigated conditions. However, it is more frequent in dryland farming and areas where irrigation is not assured.

A crop receiving balanced nutrition is able to explore a larger volume of soil in order to access water and nutrients. Plants facing moisture stress can also suffer from nutrient stress owing to the very close association between water and nutrient availability. According to Vlek and Vielhauer (1994), the main stress in relation to N management is probably the uncertainty of rainfall where irrigation is not available. Where rainfall is excessive or very intense, N is subjected to leaching or denitrification, while with drought it has a tendency to remain in the soil, unutilized by the crop.

P has a marked effect on root growth. Hence, crops deficient in P are not able to access water from deeper soil layers owing to poor root development. Therefore, such crops are more susceptible to drought than crops with adequate P and, hence, a well-developed root system. In contrast, crops overfertilized with N develop too much vegetative growth relative to the root size. This results in rapid water loss from the plant canopy, which depletes soil water faster than does a crop receiving balanced fertilization. Such crops are very susceptible to drought. Where the situation is not remedied by irrigation or timely rains, the net result is a large drop in yields. In legumes, moisture stress retards nitrate reductase activity, protein synthesis and N fixation severely.

K has an osmotic role in the plant that enables the plant tissue to hold on to its water. The movement of K in and out of the guard cells that surround the stomata on plant leaves is responsible for the opening and closing of these cells, which greatly assists in reducing moisture loss when the plant encounters moisture stress. Where plants are deficient in K, the stomata cannot function properly and the water loss from plants can be very high. Application of K has been shown to enhance the drought resistance of plant under moisture stress. During recovery from moisture stress, K can help the plant to maintain higher growth rates.

Tolerance of plants to lodging

Lodging or displacement and breaking of the stem from its upright position are common in several crops, especially cereals and grasses. Depending on the severity of lodging, the effect may be permanent or reversible to a certain extent. Crucial growth stages in cereals that are associated with yield loss as a result of lodging are heading and early grain-formation periods. Lodging in the case of traditional tall varieties of rice and wheat under N fertilization and their low genetic yield potential were some of the major reasons for the development of dwarf, stiff straw HYVs. These HYVs had higher yield potential that could be realized because these could also respond to higher rates of N application without lodging.

Lodging is particularly severe on windy days where plants with weak stems contain high levels of N. It is an interactive effect of plant type, environmental conditions, soil texture and nutrient management. Plants low in K are susceptible to lodging because they have thinner stems as a result of insufficient K. Lignification of the vascular bundles in stems is impaired under K deficiency. Such plants generally have weak stems. Plants well supplied with K have thicker stems and greater stem stability. Resistance to lodging is basically governed genetically, but adequate K supply decreases the tendency to lodge. The role of K in enhancing plant resistance to lodging has been well documented in several crops such as maize, rice, wheat and oilseed rape (Kant and Kafkafi, 2002).

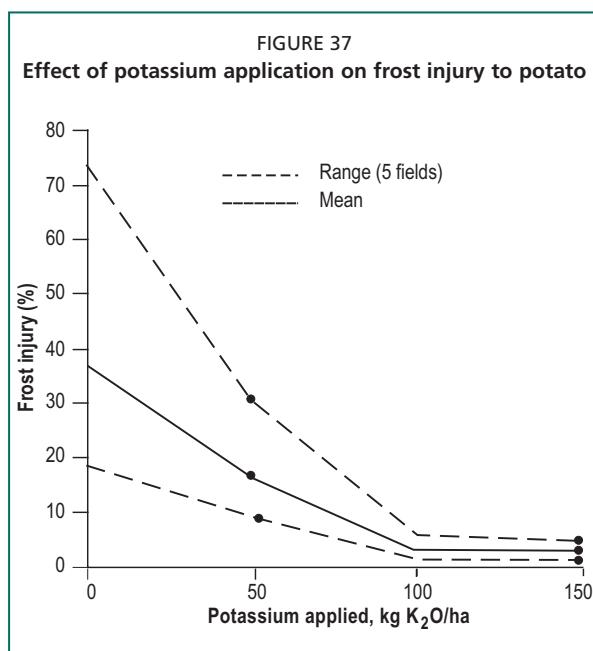
Tolerance of plants to salinity and alkalinity

In saline and alkaline soils, exchangeable Na is present in very large amounts compared with exchangeable Ca and K. Na is not an essential plant nutrient. There are indications of an association between the tolerance of a crop or a crop variety to salinity and its K status. Salt-tolerant crops are generally found to contain more K than crops susceptible to salinity. It has been shown that crop varieties that can absorb K in preference over Na are relatively more tolerant to salinity and alkalinity (Rana, 1986).

In a comparison between a salt-tolerant wheat variety (Kharchia) and a salt-sensitive variety (HD 4530), it was observed that both the varieties produced similar yields at an ESP of 7 percent. However, at an ESP of 43 percent, Kharchia still produced 2.5 tonnes of grain per hectare whereas HD 4530 yielded 0.75 tonnes/ha. The ratio of Na/K absorbed at 43 ESP was 0.43 in Kharchia and 2.59 in HD 4530. This indicates that Kharchia was capable of absorbing more K and excluding Na, but that HD 4530 was unable to restrict Na uptake (Joshi, 1980). In tomatoes, the K^+/Na^+ selectivity ratio was also higher in the salt-tolerant variety than in a non-tolerant variety (Kant and Kafkafi, 2002). These results suggest that maintaining adequate levels of K and K^+/Na^+ ratios in plant cells is essential for normal growth under saline conditions.

Tolerance of plants to cold

Nutrients can have both positive and negative effects on cold tolerance. Plants that have been overfertilized or those receiving imbalanced nutrition produce soft leaf



Source: Grewal and Sharma, 1978.

tissues that are susceptible to cold and frost damage. K has a key role in regulating cell sap concentration and this helps plants tolerate cold stress caused by very low temperatures. Potato plants well supplied with K have been found to withstand frost better than plants low in K. In the northern plains of India, the frost injury rate was 36 percent in potatoes grown without K application, 16 percent at an application rate of 50 kg K₂O/ha and 2 percent at an application rate of 100 kg K₂O/ha (Figure 37). The higher K content of plants lowered the freezing point of the cell sap, enabling them to survive spells of frost. For a given crop, the susceptibility to frost also varies with the variety. K application can increase the frost resistance of the frost-sensitive varieties.

B supply is sometimes associated with reduced frost damage. The best evidence for this has come from eucalyptus and pine trees although some indications are also available for apples and grapes (Shorrocks, 1984).

Resistance of plants to pests and diseases

Of several nutrients whose role has been studied, N and K have been investigated in considerable detail. A summary of the effects of nutrients on disease and insect resistance is presented below:

- Nitrogen: Excess N results in luxuriant plant growth, which makes them more attractive to insects and susceptible to disease and leaf-feeding insects.
- Phosphorus: A good supply helps plants resist disease, particularly bacterial leaf blight in rice, possibly by balancing the adverse effect of excess N. A good P supply also provides tolerance against infections with some bacterial or fungal crop diseases (e.g. *phytophthora* of potatoes).
- Potassium: K improves disease resistance by maintaining tightly closed stomata, which prevents the entry of pathogens into leaves. It also improves stem strength, which reduces lodging, which in turn reduces insect and disease damage and crop quality.
- Calcium: Adequate Ca is reported to reduce the incidence of club root in Brassica crops.

- Boron: B-deficient plants are more susceptible to powdery mildew. Adequate B in plants reduces the incidence of club root in Brassicas.
- Manganese: Mn deficiency causes increased incidence of blast and black spot diseases.
- Copper: Cu-deficient plants are considered to be susceptible to airborne fungal pathogens.
- Chloride: Application of Cl-containing fertilizers may reduce incidence of “take-all” (root and crown rot) in wheat by inhibiting nitrate production and reducing pH at the root surface.
- Silicon: High N and low K uptake reduce Si uptake, which makes rice more susceptible to blast disease. A low silica content in leaves makes them softer and more succulent, making them susceptible to attack by leaf-feeding/sucking pests.

N and K are known to exert a profound influence on the susceptibility or resistance of plants towards many types of pests and diseases. A high N content of the leaf tissue is known to make plants susceptible to a number of diseases and attack by pests. The adverse effect of N can be neutralized to a considerable extent by providing balanced crop nutrition, particularly optimal N:K ratios. In contrast, plants deficient in K are more susceptible to disease than those that have been adequately fertilized with K. The subject has been reviewed in detail by Perrenoud (1990).

Rice plants deficient in K or with a poor N:K balance are particularly susceptible to brown spot disease, stem rot and bacterial leaf blight. The incidence of the disease may also be affected by the amount of vegetative growth. Experiments with rice have shown that the incidence of brown spot increased with N supply at all K rates. The problem was most severe where N was applied in the absence of K because the growth stimulation brought about by N resulted in an internal dilution of K and an increase in infection potential. Adequate supply of B is associated with reduced incidence of ergot disease on barley. Seed treatment with B has also been reported to provide resistance to tomato, capsicum and cabbage against damping off fungi (Shorrocks, 1984).

NUTRIENT MANAGEMENT IN DIFFERENT CROPPING SYSTEMS

Plant nutrition problems are rare where a small population utilizes a large area of fertile soil. In contrast, almost any nutrient input is justified in cases of low production levels in relation to the food and fibre demands of the population. There is a great variety of cropping systems between these two extremes, each of which requires different system of nutrient management. All cropping systems have limitations imposed by natural and economic conditions. The objective of optimizing nutrient management is to make the best use of soil and applied nutrients within the characteristics and demands of specific farming systems for optimal production with minimal depletion of soil nutrient status. The topics in this section are interrelated with those in the earlier section on strategies for optimizing nutrient management.

Exploitive cropping at low yield level

Historically, cropping without external nutrient application has been common in many parts of the world. Exploitation of soil nutrients basically means cultivating crops until available soil nutrients have been exhausted (mined) and the yields have declined markedly. In the end, such fields must be abandoned and left to return to natural vegetation for regeneration. A typical example of exploitation cropping is shifting cultivation used by subsistence farming in certain tropical forest areas (discussed above).

This system is exploitative because nutrient losses are not compensated for by input. Nevertheless, it is stable to a certain extent as long as there has been no serious soil deterioration during the cropping period and there is sufficient land available for long regenerative phases under natural vegetation. For this to happen, there needs to be about seven times more land available than is actually needed to support the population. The poor reputation of shifting cultivation as a misuse of soil resources is mainly a consequence of the deviation from the original concept by shortening the forest fallow period and, thus, not allowing the soil enough time for regeneration. This mostly occurs as a result of an increased population pressure. With increasing populations, such systems need to be replaced by more stable and productive types of farming systems.

Sustainable agriculture at low to medium yield level

The concept of sustainable agriculture has gained a high priority. Sustainable agriculture has already been defined and described in Chapter 2. It involves the successful management of resources for agriculture to satisfy human needs while maintaining or enhancing the quality of the environment and conserving natural resources. Systems of this kind involve complex interactions and require integration of all production factors.

A prominent concept for sustainable agriculture is low-input sustainable agriculture (LISA). LISA is supposed to optimize the management and use of internal production inputs (mainly on-farm nutrient resources) in order to obtain satisfactory and sustainable crops yields and profitable returns. LISA is a subtype of organic farming. It is a production at the lower end of the crop response curve and not expected to meet the food and fibre need of heavily populated countries where most of the available arable land is already being farmed. With continuous growth in population and a near stable agricultural area, LISA would hardly be capable of providing adequate food and fibre for the expanding population.

Low-input agriculture and its associated low to medium productivity may be required for compelling natural and economic reasons. Extensive sustainable agriculture (low input, low output) in vast areas of developing countries is an example. It may also be deliberately promoted and practised for ideological reasons such as biofarming or ecofarming in developed countries. It is certainly more suitable for subsistence agriculture, for the production of high-value produce demanded by a section of the population, and for products with a “niche” market rather than for meeting the food needs of the population as a whole.

In areas with severely yield-limiting factors as in dryland farming areas, extensive farming with low input and low to medium yields still has its place. The main emphasis in this type of system lies in the use of mobilized soil nutrients and internal nutrient cycling via organic substances. However, complete cycling is difficult to achieve because of unavoidable losses. Typical examples of this approach are small subsistence farms with no or little means for nutrient input. In other systems, fertilizer input is deliberately kept low as its efficiency is known to be low under stress conditions induced by water shortage and periods of drought. Harvesting and recycling of rainwater on or off the farm holds the key to optimizing crop nutrition and increasing crop yields.

Intensive sustainable agriculture at high yield level

Sustainable agriculture cannot be equated with subsistence agriculture for the vast majority of cropland in the world. Sustainability is by no means confined to low-input conditions but can be achieved at any level of production where inputs and outputs are in balance and the best land-use practices are followed. Such systems could be called adequate-input sustainable agriculture (AISA). As demonstrated in Western Europe and elsewhere, high but adequate rates of nutrient application result in sustainable production with high yields without significant adverse effects on soil fertility or the environment. Farming systems of this kind are rather diverse, ranging from rainfed to irrigated areas, but they have many similarities in terms of nutrient management.

Research results from many parts of the world show that high crop yields are sustainable through balanced and integrated nutrient management supported by suitable amendments to address problems such as excess acidity or alkalinity. There is hardly any challenge or role for modern science and technology if sustainable agriculture is to be restricted to low-productivity subsistence farming.

The long-term experiments at Rothamsted in the United Kingdom have been in existence for more than 150 years. Results of continuous cropping for more than 100 years (1952–1967) show an average wheat yield of only 1 tonne/ha in an untreated plot and about 2.5 tonnes/ha in plots receiving either 35 tonnes FYM/ha or only fertilizers at the rate of 146 kg N + 75 kg P₂O₅ + 100 K₂O/ha.

In the United States of America, the oldest experimental plots, known as Morrow Plots, have been in existence since 1876 at the University of Illinois. Based on results obtained over a period of more than 100 years from these plots, Darmody and Peck (1993) concluded that well-treated soils could provide food and fibre continuously at high levels. Average maize grain yield in the best rotation coupled with optimal fertility management was 8.6 tonnes/ha compared with 2.2 tonnes/ha in untreated plots under continuous corn. These results contain a significant message for countries that are continuously striving to meet the food and fibre needs of an expanding population from a resource base that is expanding either slowly or not at all.

In a long-term experiment at Aiza, Fukushima Prefecture, Japan, a set of fertilizer treatments with and without organic manures and amendment were

initiated in 1920. Even in the 1980s, the untreated control plot was able to sustain paddy yields of about 4 tonnes/ha, but plots receiving only NPK through fertilizers produced twice as much. Nearly 70 years of continuous fertilizer use have not had a negative effect on the physical, chemical and biological properties of this paddy soil (von Uexkull and Mutert, 1993).

In a study to evaluate changes in the properties of agricultural soils over a 60-year period, researchers in California, the United States of America, analysed 125 soil samples collected in 2001 for which reference samples taken around 1945 were also available. By comparing the analytical values obtained from the two reference years, their overall conclusions were that while increased clay percentage may indicate accelerated soil erosion, the soils of California have maintained their chemical quality over the past 50–60 years (DeClerck and Singer, 2003).

Results from a number of long-term field experiments were started in India in the early 1970s using high-intensity crop rotations involving 2–3 crops in succession per year under irrigated conditions. On the whole, these experiments have shown that high levels of crop productivity (8–12 tonnes grain/ha/year) can be sustained by integrating optimal and balanced fertilizer application rates with 10–15 tonnes FYM/ha/year. These experiments have established that fertilizer is the key input for increasing crop productivity, but also that the integrated use of fertilizers and FYM or lime where needed give higher and more sustainable yields as it could also correct some micronutrient deficiencies and improve soil physical and biological properties (Swarup, 2000).

Even under rainfed dryland conditions, medium to high crop yields can be sustained through an integrated use of fertilizers and organic manures. Results of a nine-year field trial with dryland finger millet in the red soils at Bangalore, India, show that the best yields were obtained when recommended rates of fertilizer were applied in combination with 10 tonnes FYM/ha. It was only at this input level that grain yields of 3 tonnes/ha and above could be harvested in eight out of the nine years (Table 34). A considerable portion of the yield potential would have been lost if either of these inputs had been omitted.

The goal of intensive sustainable agriculture at high yields is to utilize, as far as possible, the yield potential of high-yielding crops by eliminating all nutritional constraints through INM including fertilization and maintaining high soil fertility,

TABLE 34

Effect of fertilizers and FYM on the productivity and stability of dryland finger millet over nine years at Bangalore, India

Annual treatment	Mean grain yield (kg/ha)	Number of years in which grain yield (tonnes/ha) was			
		< 2	2–3	3–4	4–5
Control	1 510	9	0	0	0
FYM (10 tonnes/ha)	2 550	1	6	2	0
Fertilizer 50–50–25 (kg/ha N–P ₂ O ₅ –K ₂ O)	2 940	0	5	4	0
FYM (10 tonnes/ha) + 25–25–12.5 (kg/ha N–P ₂ O ₅ –K ₂ O)	2 900	0	6	3	0
FYM (10 tonnes/ha) + 50–50–25 (kg/ha N–P ₂ O ₅ –K ₂ O)	3 570	0	1	5	3

while simultaneously protecting the crop against disease and insect damage. However, there is a negative aspect of nutrient management under such systems. This happens where there is heavy reliance on the fertilizer input while neglecting the soil nutrient reserves and those available in various organic sources. This tends to occur where cheap chemical fertilizers are readily available. This has led to the public misconception that intensive cropping is essentially a “nutrient-wasting” system.

Sustaining crop productivity at a high yield level has proved possible in many progressive agricultural areas, even in parts of so-called developing countries such as Punjab State in India. The dependence on fertilizers for adequate food and fibre production continues to remain because of continuous growth in human population and little expansion in the net cropped area. Food production can be enhanced by better nutrient cycling and prevention of losses. However, the food demands of an increasing population cannot be met only from organic sources or from fertilizers alone. They require an active pre-planned INM approach. As part of integrated crop production, INM will be a decisive factor in attaining the goal of sustainable high yields and profitable crop production without negative effects on the environment.

Harnessing BNF is an important component of INM and this is not confined to a particular cropping system or productivity level. Although considerable amounts of N can be fixed by legumes, whether or not this results in a buildup of soil N or the N nutrition of the following non-legume crop, depends on the amount of N fixed, the amount of N removed in the crop products and the residues. In many cases, growing a legume in a rotation contributes significantly to the N nutrition of the following crop. Where crop yields are high and a large amount of N is removed in the harvested product, the effect may be small or even negative. In grass-legume pastures, the transfer of N from the legume to the pasture is small, and the N passes from the legume to the grass primarily in the manure and urine from the grazing animal or after the decomposition of legume residues.

Biofarming and ecofarming

Biofarming and ecofarming are forms of organic farming. They refer to special farming systems that exclude the application of manufactured mineral fertilizers or pesticides, but use natural minerals such as PR, animal manures, compost and legumes as nutrient sources. Such systems place considerable emphasis on nutrient cycling. It is claimed that with this production system a better food quality is produced and that the environment is better protected against unwanted pollution from agricultural chemicals. The system is workable because of the higher produce prices realized, which compensate for the generally lower yields obtained.

The general term biofarming denotes a group of similar and yet different systems of nutrient supply. Biological dynamic agriculture (the oldest, orthodox type of system initiated by Steiner in 1924) excludes all kinds of commercial mineral fertilizers. In contrast, major groups (e.g. Bioland) exclude mainly water-soluble mineral fertilizers, especially N fertilizers, but permit other major

nutrient sources if they are natural products such as PR, crude salts of K and lime. Micronutrients are allowed only where there is an obvious deficiency. The rejection of water-soluble N fertilizers, whether nitrate-containing ones or urea, has no scientific basis. It is an ideological concept based on the philosophy of going back to nature.

The general features of permitted practices under organic farming as set by the International Federation of Organic Agriculture Movements (IFOAM, 1998) are:

- Inputs manufactured by chemical processes should not be used.
- Water-soluble N and P fertilizers are avoided as a matter of principle.
- Soluble potassium sulphate and micronutrients are permitted provided a threatening deficiency is documented through analysis.
- PR and other natural minerals with a low solubility can be used.
- Weeds are removed or damaged by mechanical soil treatment or the use of flame.
- Extensive crop rotation and intercropping are adopted, while monocultures are avoided.
- Herbicides and synthetic pesticides are prohibited and genetic engineering is not accepted practice.

Although the claims for superior quality food by avoiding chemical fertilizers and chemical crop protection have not been substantiated, a limited number of consumers support this production of so-called “natural” food by paying premium prices. The further claim that these types of biofarming and ecofarming systems cause less pollution of water bodies because they do not use any chemical fertilizer input should be questioned. Although a lower amount of N leaching is often achieved per unit of land, it rarely holds true per unit of crop produced, especially because almost twice the area of land is required for biocropping and ecocropping than with conventional farming.

However, organic farming does have a place as one of the many farming systems. It is more of a class enterprise rather than a mass enterprise. It is best suited for producing organically grown produce for which consumers are prepared to pay the higher price demanded. Based more on belief than on fact, it automatically favours the exclusion of certain technologies and inputs because these go against the belief. This approach conventionally ignores the existence and operation of nutrient cycles in soils through which mineral and organic nutrient forms are interconvertible (and beneficially so because plant roots feed only on mineral nutrient forms regardless of whether these are derived from mineral or organic sources). Such compartmentalization of nutrients into organic (natural) and mineral (artificial) overlooks the basic fact that these two forms not only coexist but are interchangeable in soils.

Organic agriculture faces the same environmental and sustainability problems with crop nutrient management as does mainstream agriculture: emissions of ammonia and nitrous oxide, nitrate leaching, energy use, and depletion of PR resources (Laegreid, Bockman, and Kaarstad, 1999).

Optimizing nutrient management in diverse cropping systems

There is a multitude of cropping systems in use throughout the world. These range in intensity from raising one crop per year (as happens in many rainfed dryland areas) to 3–4 crops per year in irrigated/assured rainfall areas on the same piece of land. Wherever adequate rainfall or irrigation is available and the climate permits, raising two grain crops in succession within a year is possible. In many areas, the whole cropping system or rotation is completed within one year. In other areas, a given system may be rotated after 2–3 or more years. Only some of the nutritional features of the main types of cropping systems are discussed here.

Annual crops in different rotations

Short rotations that include crops such as rice, wheat, maize, oilseed rape, barley, vegetables and fodders are highly nutrient demanding and, therefore, rely mainly on high external nutrient input. Except for N, especially where no legumes are involved, nutrient management is more concerned with the whole rotation than with individual crops. Fertilizers are applied to maintain a high nutrient supply utilizing both the direct (fertilized crop) and the residual effects. This is sometimes referred to as “rotation fertilization”. For example, in temperate climates, substantial amounts of mineral N often remain in the soil after oilseed rape, which is usually followed by winter wheat. The wheat crop utilizes the residual nutrients in autumn before the main leaching period. Longer rotations, which include crops such as sugar beet, potatoes or even legumes with their extra gain of N, often have more soil tillage, soil cover and, thus, nutrient mobilization than cereals.

One of the most intensive and nutrient-demanding rotations in parts of South Asia is the rice–wheat rotation. In India, this rotation is practised on more than 10 million ha, primarily in the northern alluvial plains. Under optimal management, grain yields of 8–12 tonnes/ha/year can be harvested. Optimizing nutrient management in this system includes the application of NPK and other required nutrients such as S and Zn. The wheat crop must receive its optimal rate of P application while rice can benefit to a considerable extent from the residual effect of P applied to wheat. On highly P-deficient soils, P must be applied to both crops. Incorporation of green gram residues after picking the pods before planting rice is an effective green manuring practice in this system. In general, research recommendations provide for application of the full recommended rates of fertilizer to the wheat crop, while 25–50 percent of the recommended fertilizer to rice can be saved through the use of 10 tonnes/ha FYM, *Sesbania* green manure and crop residues (Yadav *et al.*, 2000). Information is also becoming available on INM in this highly intensive system (Table 35).

Annual crops in monoculture

In several tropical and subtropical areas, high-intensity monoculture is practised wherever the rainfall is well distributed or where adequate irrigation is available.

Wetland rice has its special problems of nutrient management owing to the strong reducing conditions of the submerged soil in which several mobilization

TABLE 35

Examples of INM packages and their comparison with fertilizer recommendations for rice–wheat cropping in different agroclimate regions of India

Region	Mineral fertilizer recommendation (kg/ha)	Integrated nutrient management recommendation (kg/ha)
Trans Gangetic Plain	Rice: 120 N + 60 P ₂ O ₅ + 60 K ₂ O + 20 zinc sulphate Wheat: 180 N + 60 P ₂ O ₅ + 30 K ₂ O	Rice: 60 N + 30 K ₂ O + 10 tonnes/ha FYM or poultry manure Wheat: 150 N + 30 P ₂ O ₅ (through SSP) + 30 K ₂ O + <i>Azotobacter</i> or <i>Azospirillum</i> + PSB
		Rice: 90 N + 30 K ₂ O + 10 tonnes/ha FYM or green manuring with <i>Sesbania/Leucaena</i> lopping Wheat: 90 N + 60 P ₂ O ₅ (through SSP) + 30 K ₂ O
Upper Gangetic Plain	Rice: 120 N + 60 P ₂ O ₅ + 40 K ₂ O + 20 zinc sulphate Wheat: 120 N + 60 P ₂ O ₅ + 40 K ₂ O + 40 S	Rice: 90 N + 30 K ₂ O + 10 tonnes/ha FYM or green manuring with <i>Sesbania/Leucaena</i> lopping Wheat: 90 N + 60 P ₂ O ₅ (through SSP) + 30 K ₂ O
		Rice: 50 N + 30 P ₂ O ₅ + 20 K ₂ O + green manure (green gram stover) + 20 zinc sulphate in calcareous soils Wheat: 90 N + 60 P ₂ O ₅ + 30 K ₂ O + 10 tonnes/ha FYM or Rice: 75 N + 45 P ₂ O ₅ + 30 K ₂ O + 15 kg/ha BGA + 10 tonnes/ha FYM + 20 zinc sulphate in calcareous soils Wheat: 100 N + 65 P ₂ O ₅ + 30 K ₂ O
Middle Gangetic Plain	Rice: 100 N + 60 P ₂ O ₅ + 40 K ₂ O Wheat: 120 N + 80 P ₂ O ₅ + 40 K ₂ O	Rice: 50 N + 30 P ₂ O ₅ + 20 K ₂ O + green manure (green gram stover) + 20 zinc sulphate in calcareous soils Wheat: 90 N + 60 P ₂ O ₅ + 30 K ₂ O + 10 tonnes/ha FYM or Rice: 75 N + 45 P ₂ O ₅ + 30 K ₂ O + 15 kg/ha BGA + 10 tonnes/ha FYM + 20 zinc sulphate in calcareous soils Wheat: 100 N + 65 P ₂ O ₅ + 30 K ₂ O
		Rice: 40 N + 45 P ₂ O ₅ + 30 K ₂ O + 10 tonnes/ha FYM or green manure + 10 tonnes/ha <i>Azolla</i> or 10 kg/ha BGA + 20 zinc sulphate Wheat: 90 N + 45 P ₂ O ₅ (through SSP) + 45 K ₂ O
Lower Gangetic Plain	Rice: 80 N + 60 P ₂ O ₅ + 40 K ₂ O Wheat: 120 N + 60 P ₂ O ₅ + 60 K ₂ O	Rice: 40 N + 45 P ₂ O ₅ + 30 K ₂ O + 10 tonnes/ha FYM or green manure + 10 tonnes/ha <i>Azolla</i> or 10 kg/ha BGA + 20 zinc sulphate Wheat: 90 N + 45 P ₂ O ₅ (through SSP) + 45 K ₂ O

Source: Sharma and Biswas, 2004.

and fixation processes take place (Chapter 5). A major unresolved problem is the low recovery of fertilizer N, which is mainly applied through urea in these systems. Usually, only 30–50 percent of the added N is taken up by the crop compared with about 70 percent in intensive well-managed wheat cropping. The low N efficiency is a consequence of N losses by various routes.

Extensive on-farm trials suggest that the adoption of appropriate crop and nutrition management practices can minimize the effects of diminishing returns at increasing N application rates mainly on account of N losses. In order of importance, the limiting factors that smallholder rice farmers using prill (or granular) urea can address are: (i) too few split applications, resulting in substantial N losses and consequent inadequate N supply to meet crop requirements at various growth stages; (ii) cultivars that may be insufficiently N responsive; and (iii) inadequate initial plant population. A multilocation on-farm trial/demonstration project on irrigated rice (1995–98), funded by Japan and implemented by FAO in Indonesia, the Philippines and Malaysia, demonstrated that deep-placed USG enables a 21-percent N saving in comparison with 70 kg/ha N applied as prill urea in three splits (FAO, 2003c). Urea coated with Nimin, a commercial extract from neem (*Azadirachta indica*) seed, has been widely tested, especially in India. This reasonably inexpensive biological product shows great promise for resource-poor farmers, with an average yield increase of 5–10 percent over uncoated prill urea. Supergranules made with Nimin-coated urea and placed deep show further improvement over the USG technology.

In many rice-growing areas, wherever the climate permits, 2–3 rice crops can be raised in succession within a year. For example, in India, rice–rice annual rotation is practised on almost 6 million ha. Supply of N through BGA and *Azolla*/ *Anabaena* symbiotic systems has some promise and could potentially replace a portion of N fertilizer.

Annual crops with short-term fallow

Fallowing may be required for weed control in humid climates or for water storage in the soil in dryland farming. In the absence of crop removal, fallowing also conserves mobilized soil nutrients, thus providing an extra nutrient supply for the next crop. Fallows can be bare or with a plant cover, depending on the main purpose. Bare fallow is a period of nutrient and water accumulation. In overpopulated, land-scarce countries, land is rarely left fallow by choice. It is more a consequence of the farmer's inability to raise an additional crop under low rainfall or inadequate stored soil moisture. The vegetation cover during the fallow period can be used effectively as a mulch or even as a green manure.

Multiple-cropping systems

Multiple cropping refers to the cultivation of two, or often more than two, crops on the same field in a year. The concept of multiple cropping includes cropping practices where sole or mixed crops are grown in sequence, simultaneously one after another, or with an overlapping period. A distinction is made between sequential cropping and intercropping. Sequential cropping can involve growing two, three or four crops a year in sequence or ratoon cropping. Intercropping involves mixed/row/strip intercropping (simultaneously) or relay intercropping (overlapping).

Optimizing plant nutrition in multiple-cropping systems revolves around:

- adjusting for residual effects of nutrients such as P, S and micronutrients (e.g. applying P on priority to wheat and green manure to rice in a rice–wheat rotation, and FYM on priority to maize in the maize–wheat rotation);
- prioritizing the application of fertilizers to those crops in the system that have a poor root system and are poor users of applied nutrients (e.g. potato in a potato–maize system);
- planning for a short-duration catch crop that can feed on residual fertility in between two main crops (e.g. green gram in a maize–wheat–green gram annual rotation);
- practising INM keeping in view crop characteristics (e.g. green manuring where possible before planting rice or inoculation of the rice field with BGA/ *Azolla* in rice-based cropping systems);
- phasing of fertilizer application among crops in a rotation so that maximum direct plus residual gains are obtained (e.g. P application on priority to wheat in rice–wheat, maize–wheat or sorghum/millet–wheat rotations, S application to an oilseed crop in an oilseed–cereal rotation);

- in mixed cropping, such as with cereals and legumes, the fertilizer application is primarily determined by the cereal, and the legume seed can be inoculated with *Rhizobium* culture;
- nutrient management in multiple-cropping systems should be finally decided by the economics of the yield response to various nutrient applications, particularly where the component crops fetch different market prices (e.g. a yield response of 1 tonne oilseed is more valuable than a yield response of 1 tonne cereal).

Depending on the strategy of nutrient management used, the gains from multiple cropping can vary considerably. Results from several long-term experiments employing multiple-cropping rotations for example have shown that: (i) intensive cropping with only N input is a short-lived phenomenon; (ii) sites that were initially well supplied with P, K or S became deficient over a period of time when continuously cropped using N alone or S-free fertilizers; (iii) in most situations, optimal fertilizer application + 10–15 tonnes FYM/ha/year was required in order to sustain crop yields; (iv) soil fertility status was improved or depleted depending on input–output balances as well as by soil properties; and (v) fertilizer rates considered as optimal still resulted in nutrient depletion from the soils at high productivity levels and in the process themselves became suboptimal application rates.

These experiments demonstrated that the same field that produced 1 300 kg grain/ha from two crops grown without fertilizer application could give 7 424 kg grain/ha when the crops received optimal application of the nutrients required (Nambiar, 1994).

OPTIMIZING NUTRIENT MANAGEMENT IN DRYLAND AND IRRIGATED FARMING

The following sections discuss some aspects of nutrient management under varying regimes of water availability. These range from dryland farming, to conventional irrigated farming and, finally, to flooded soils used for wetland rice production. The aspects discussed are general and applicable to various types of cropping systems described above. These all point to the need for integrated management of nutrients and water in order to optimize the efficiency of and returns to nutrient application.

Nutrient management in dryland farming

In rainfed dryland farming systems, the yield is usually limited by a shortage of water, rainfall being not only scarce but also variable and, thus, unreliable. The main nutritional problem is the shortage of total and available N owing to the low SOM content. In order to make the best use of the scarce soil N resource at sowing time, the N requirement of the crop should be adjusted for the nitrate flush occurring from rapid mineralization at the onset of the rainy season. In practice, this is not easy because of the uncertain onset of the rainy season. There can also be some upward movement of nitrate from the subsoil by evaporation.

The natural N supply may be sufficient for low yields, e.g. 1–3 tonnes grain/ha. However, for medium yields, additional N sources such as farm waste materials or even mineral N should be added where there is sufficient moisture. Grain yields of 3–4 tonnes/ha are sustainable under dryland farming where the system is managed properly, as shown in Table 33. The growing of grain and fodder legumes is widely practised in such areas. In order to derive maximum benefit, adequate phosphate application should be ensured and the legume should be inoculated with an appropriate *Rhizobium* strain in order to maximize the gains from BNF.

Mulching is difficult in these environments because of a shortage of organic matter. However, where available, it can be used for soil protection or mixed into the topsoil as a nutrient source. In very hot climates, mulching can also reduce water loss from the soil and reduce soil temperature. An increase in the very low SOM level is desirable, but the possibilities are limited because of high mineralization rates. The application of organic substances is often limited by competitive use of crop residues, etc. for fodder, fuel and roofing. Another possibility to conserve the natural nutrient supply and plant available water is the use of a bare fallow. However, this may reduce SOM and risk soil losses from erosion.

In addition to N, the P supply is often insufficient either because to low available P in the soil or slow mobility towards plant roots. As P is especially required for root growth and as deep rooting may be decisive for crop survival during dry spells, a good P supply is important beyond its actual role as a nutrient. A good K supply is also essential to reduce transpiration losses from crops. However, for dryland farming on many arid soils, there is generally sufficient available K for at least low to medium yield levels. The same holds true for Mg and S.

Poor availability of micronutrients in neutral to alkaline soils results in a frequent deficiency of Fe and/or Zn. Some improvement in their availability can be made by using strongly acidifying N fertilizers such as ammonium sulphate and, to a lesser extent, urea. However, ammonia volatilization under such systems should be minimized.

Considerable production potential still exists in dryland areas but it can only be realized by combining moisture conservation and the recycling of rainwater with optimal nutrient supply. Special climate and biotic stress factors must be taken into account while managing such soils. However, cropping systems in semi-arid regions that use common agricultural practices may not always be sustainable. They can potentially be made so by the application of the existing research knowledge for INM and the harvesting of the rainwater in combination with farmers' accumulated experience.

Nutrient management in irrigated farming

Irrigation supplies a vital input (water) for crop production and also brings some nutrients with it. It also stimulates the mineralization of SOM and the solubilization and transport of nutrients from sparingly soluble to available inorganic forms.

Irrigation results in considerable dilution of the soil solution. This has the advantage of lowering the osmotic pressure, but the disadvantage of lowering the concentration of nutrients, which cannot be replenished rapidly. There is a relative increase in the concentration of monovalent cations such as K^+ in the soil solution caused by cation exchange. The resulting increase in K supply may temporarily reduce the supply of Mg. The Ca concentration also decreases, but this has no detrimental effects in view of its large total supply.

When a soil is saturated, the pore space occupied by air also becomes filled up with water, creating anaerobic conditions. Where the saturation is temporary and followed by deep percolation, this leads to leaching of soluble nutrients. Where it is prolonged or results in waterlogging, chemically reduced conditions set in. This results in more intensive mobilization and re-supply from mineral nutrient reserves, especially at high temperatures. Nutrients such as Fe and Mn are converted from unavailable to available forms because of the reduced conditions. As the intensity of the reduction varies, so does the availability of these nutrients, resulting in the appearance and disappearance of Fe-deficiency symptoms during the irrigation cycle. Where the redox potential is lowered permanently, iron oxides can be reduced to such an extent that Fe toxicity can occur.

Apart from the flooded-rice soils, there are dry periods in between wet periods in most irrigated soils. These could be caused by a high rate of deep percolation, high evapotranspiration loss or inadequate supply of irrigation water. The drying out of the soil during the dry phase between irrigation periods increases the soil solution concentration by evapotranspiration but reduces the rate at which these nutrients can be transported to the roots. The concentration of divalent cations such as Ca^{2+} increases relative to the monovalent cation K^+ .

More severe drying finally results in immobilization of mobile nutrients, i.e. conversion from the soluble and mobile forms to the reserve fraction. Phosphates precipitate, Fe and Mn are oxidized and, thus, are less available (reverse of what happens during flooding). K is adsorbed more strongly, the degree of which depends on the content of clay minerals in the soil. However, these temporary deficiencies at the end of the dry phase may be compensated for by mineralization of plant nutrient reserves. These features of irrigated soils must be taken into account when determining optimal nutrient application rates as the relatively high production level must be supported by more intensive fertilization. Fertilizer can also be supplied with the irrigation water via fertigation (Chapter 7). Many aspects covered in the above section on integrated nutrient–water management are also applicable to this section.

Grasslands or permanent pastures and meadows

The growing of either grassland or arable fodder crops for animals results in a special internal farm nutrient cycle that benefits arable crops. In these systems, the export of plant nutrients in meat or milk is lower than with harvested plant products. Fertilization of grassland has two main goals: a high yield of palatable fodder for substantial production of milk, meat and wool; and good health

(including good fertility) of the domestic animals. The fertilization required depends on the production target (e.g. amounts of milk and meat), on the soil nutrient supply and on the grassland utilization system, such as grazed or fodder cut for conservation.

Principles of grassland nutrition

For proper animal nutrition, grassland fodder should contain large amounts of protein, carbohydrates (energy carriers), vitamins and flavouring substances. It should also have optimal amounts of mineral nutrients but no toxic organic substances or excess inorganic nutrients.

Two different aspects must be considered for optimal nutrient supply to plants and animals. First, an optimal mineral composition of the plant not only increases the content of valuable organic substances, such as amino acids, proteins, carbohydrates and vitamins, but also the supply of minerals. Only a limited amount of essential minerals can be given to the animals directly. Second, the mineral requirements of plants and animals differ in some respects. These are:

- similar requirements for plants and animals: P, S, Ca and Mg;
- larger requirements by plants than animals: K, B and Mo;
- larger requirements by animals than plants: Na, Cl, Ca, Mg and some micronutrients;
- required only by animals: I, Co, Se and Cr.

A knowledge of the fodder composition (protein and mineral nutrients) at the time of pasturing or haymaking is an essential precondition for the efficient production of valuable fodder. Milk production requires large amounts of energy and protein as well as a high mineral content. Meat production initially requires fodder that is very rich in protein, but later more energy is required. Fertilization also serves to control the botanical composition of the pasture. The proportion of grass in the pasture increases with increasing amounts of N and K, while the proportion of legumes decreases.

Soil reaction can and should be slightly lower than on arable fields of the same soil texture. In fact, slight to moderate acidity is often useful. Where liming is required, the reaction should stay below neutral.

Thus, the target for nutrient application of grassland consists of supplementing the natural concentrations until the optimal supply range is reached (Table 36). Luxury supplies, or even excess, may lead to problems such as reduced feed intake of other nutrients or decreased absorption of minerals in the animal. The concentration of minerals in the fodder generally decreases with age owing to dilution and maturity effects. Therefore, data on concentrations must refer to a definite growth stage. For grassland, a suitable reference stage is shortly before the beginning of flowering.

Some aspects of nutrient supply in grassland

Most intensively managed grasslands are short in N supply, and N fertilization is almost always required for high yields. The amount of N needed depends on:

TABLE 36
Optimal mineral concentrations of grassland fodder on a dry-matter basis

Name	Major nutrients		Name	Micronutrients		Name	Beneficial nutrients for animals (g/g)
	A ¹ (%)	B ² (%)		A ¹ (g/g)	B ² (g/g)		
P	0.3	0.4	Fe	50	60	I	0.3
Ca	0.5	0.7	Mn	40	60	Co	0.1
Mg	0.15	0.25	Zn	20	30	Se	0.1
K	2.0	2.0	Cu	5	8		
Na	-	0.2	Mo	0.3	0.3		

¹ For high grass yield and medium milk production.

² Fodder for highly productive cows, i.e. 20 litres milk/day, intake of 12 kg of dry matter.

Source: Finck, 1992 (data from various sources).

growth conditions, the desired yield level and the protein content of the fodder. For 20-percent protein, 3 percent N must be in the dry matter, which results in a requirement of 30 kg N/tonne of dry matter. On average, 1 kg of N produces 25 kg of dry matter. In many areas, legumes supply the N to the system and grazing management is required to maintain them in the sward.

The P concentration in grass should be 0.3–0.4 percent. Where P is a yield-limiting nutrient, considerable improvement can be achieved by P application. This is because it encourages the growth of legumes and, thereby, the N supply to grasses. The choice of the P form is of minor importance, especially on moist grassland with a good mobilization capacity. On strongly acid P-sorbing soils, PR is recommended.

The natural supply of K should suffice for high fodder yields in many situations. However, where the forage is cut and removed, K may need to be applied. Large amounts of K can be supplied with animal slurry, but excess K can decrease the supply of Mg. Potassium chloride is the preferred source of K.

The large Ca concentration required cannot be attained easily by grasses, which often contain only 0.4 percent Ca. Many herbs and especially legumes contain more than 1 percent Ca. The Ca:P ratio should be 1.5–2:1. The Ca concentration can be increased by liming, but this should only be done up to the optimal pH value, which is somewhat lower than seven.

Mg is often a limiting factor for grass growth on acid soils. Animals can suffer from grass tetany (hypomagnesaemia) where the Mg concentration of the grass is very low or Mg absorption from the fodder is inhibited. The critical Mg concentration in the fodder for high-performance dairy cows is about 0.25 percent. Moreover, the ratio K:(Ca + Mg) should be less than 2.2:1 (expressed in equivalents per kilogram). Magnesium sulphate or any other Mg source can be used.

A deficiency of Cu causes poor growth of cattle and “lick disease”. Cattle require 1 µg/litre Cu in their blood and for high milk yields; this is achieved with about 8 µg/g Cu in the fodder. Animals often prefer plants or plant parts with higher Cu concentrations. For proper Cu utilization by the animals, the Ca concentration of the fodder should be below 0.8 percent, Mo should be less than 3 µg/g, and S concentration in the range required for optimal plant growth. Cu

deficiency in grassland can usually be corrected for several years by adding 3–5 kg Cu/ha through any Cu-containing fertilizer.

Sufficient Mn, even for high requirements, is generally supplied where the pH value of grassland remains in the slightly acid range. However, on neutral soils the high Mn concentrations required for high milk yield and animal fertility may not be reached. A simple way to increase Mn supply is through soil acidification by using acid-forming N fertilizers. Zn requirements for high milk yields are significantly greater than the Zn needs of plants. However, many soils supply sufficient Zn. Zn application is required only where the optimal Zn status is not reached. Fe, B and Mo are usually present in sufficient amounts in the fodder, but Mo may need to be applied to acid soils for better N fixation by legumes.

Some grasses absorb only small amounts of Na and contain less than 0.01 percent Na whereas some herbs, e.g. white clover, have Na concentrations of more than 0.4 percent. It does not seem necessary to cover all the Na requirements of animals via grass, but a relatively high Na concentration is desirable. Deficiencies of I and Co are rare but a shortage of Co on acid sandy soils, often together with Cu deficiency, can occur. Se deficiencies are more widespread than formerly assumed. However, care should be taken with general application of Se on all grasslands as its optimal range is narrow and high concentrations are toxic. Cr seems to be required only in extremely small amounts.

Beneficial elements, such as V, Ni, Si and bromine, which are required only in very small amounts, are generally supplied by the soils. The silicic acid in many grasses occurs in the form of needles, which may cause injury to the digestive tract of the animals.

Chapter 8 provides recommendations for the fertilization of intensively used grasslands.

Chapter 7

Guidelines for the management of plant nutrients and their sources

PRECONDITIONS FOR SUCCESSFUL NUTRIENT MANAGEMENT

Improvement in the nutrient status of soils and crops is successful with respect to yield increase as well as environmental acceptance when it is integrated into the crop production systems considering the many interactions involved. Plant nutrients should not just be added to the soil, but management practices should ensure their maximum uptake by plants. The total nutrient supply from external sources including fertilizers plus available soil nutrients should be balanced, the soil nutrient supply should be utilized without exhaustion, and external inputs should be used to the extent required. In short, the application of nutrients should be balanced, efficient and economic on a sustainable basis. Simultaneous application of all 16 essential plant nutrients is not called for except in solution cultures. Nutrients and their combinations to be applied can be indicated best through soil and plant diagnostic techniques.

Before applying nutrients, whether through organics or mineral fertilizers, it is advisable to consider the following guidelines as basic requirements for nutrient use. In addition to these, available diagnostic techniques should be fully utilized in decision-making. Plant nutrients, their role and deficiency symptoms have been discussed in Chapter 3. Chapter 4 has examined the dynamics of plant nutrients in soils along with diagnostic techniques for the nutrient status of soils and plant. Chapter 5 has described the materials that supply these nutrients. This chapter provides information on principles and practical guidelines on nutrient management, application techniques of fertilizers and other sources of nutrients such as organic manures and biofertilizers. Chapter 8 provides some illustrative nutrient recommendations for a number of field crops and grassland.

The general agronomic preconditions for successful nutrient management include: (i) selection of a high-yielding and locally adapted crop variety; (ii) proper seed-bed preparation and cultivation practices; (iii) proper sowing or transplanting to ensure optimal plant density; (iv) good soil and water management practices under both irrigated and rainfed conditions; and (v) sufficient plant protection against possible yield losses.

Basic requirements of good soil fertility

The basic requirements of good soil fertility include:

- optimal soil reaction within a practical range;
- sufficient organic matter by applying organic manures for improved soil structure, water storage capacity, nutrient supply and satisfactory activity of soil organisms;
- a stable porous soil structure with no compact layer (which restricts root growth);
- good drainage;
- water availability, especially during periods of water stress and long dry spells;
- removal or neutralization of toxic substances, e.g. in strongly acid (Al), polluted (toxic heavy metals) or saline/alkali soils (excess chloride, Na, etc.).

Soils that are very rich in a nutrient and are able to release it at an acceptable rate in relation to crop demand would generally need its application only to the extent of crop removal replacement. This calls for periodic monitoring of the soil nutrient status because the “very rich” condition does not last indefinitely, particularly under intensive cropping. At the same time, it is necessary to differentiate between nutrients that are mainly applied on a crop-to-crop basis, such as N, and nutrients that leave a significant residual effect. The latter are not to be applied to each crop but on a cropping-system basis (P, S, Mg and micronutrients such as Zn and Cu). Large applications of Mg resulting from the use of dolomitic limestone can last for several years. In deciding the frequency with which such nutrients need to be applied, the degree of their fixation by soil constituents needs to be taken into account. The system is a dynamic one and it should be managed accordingly.

Basic issues for timing nutrient supply

The application of organic manures, fertilizers and liming materials should be timed when these are most effective. Organic manures and liming materials should be applied several weeks before sowing. The same holds true for materials that need to be converted into soluble and plant available forms in the soil before they can contribute to crop nutrition. Such materials include ground PR, elemental S products and pyrites. However, leguminous green manures grown before rice can be incorporated into the puddled soil a few days before transplanting rice as their rate of decomposition is quite fast.

Fertilizers can be applied both at or before planting and during crop growth. The decision about when and how much to apply depends on: crop duration; total amount of a nutrient to be applied; nature of the nutrient, especially with regard to its transformation and mobility; availability of water; and anticipated outbreak of pests and diseases.

In general, the total amount of N is applied in 2–4 instalments starting from a basal dressing. Where the crop is raised largely on stored soil moisture, the entire N is to be applied pre-planting, preferably below the soil surface. For winter crops, N is to be applied partly in autumn but mainly in spring in 2–3 dressings. In the

case of N-deficiency symptoms in the standing crops, immediate N application via leaves or soils is suggested. Phosphate and potash fertilizers are mixed into the top layer in moderately fertile soils, especially in narrow-row crops. They are placed strategically or drilled below the seed in wide-row crops, especially in low-fertility soils and soils with high P-fixing capacity. The K needs of several fruit and vegetable crops are very high and must be met from the early stages of crop growth. S is also normally applied before planting.

Special emphasis is needed on certain nutrients for specific soils and crops. For example, legume crops generally need only a small starter dose of N in spite of their high N requirement. This is because these crops are able to procure much of their N through N fixation where conditions favour adequate nodulation and N fixation. In many grain legumes, *Rhizobium* inoculation is a standard recommended input and is given through seed-coating before planting. For nutrients such as Fe and Mn, foliar application is far superior to soil application and their application needs to be timed with crop growth.

Common mistakes in nutrient management

The implementation of optimal plant nutrition is more difficult than generally assumed. As a result, deviations from the optimal supply frequently occur. In practical agriculture, owing to many uncontrollable variables, perfect implementation of scientific findings is rarely possible. Efficient nutrient management should start by avoiding common mistakes. Some suggestions for avoiding common mistakes in nutrient management are provided below:

- Maintain the soil in good condition as the basis for high NUE. Common mistakes include: overlooking too high or too low soil pH, inadequate organic matter, and poor soil structure.
- Apply adequate nutrients in order to achieve a realistic yield level. A common mistake is to strive for an unrealistic yield level. Where excess N is given for an unrealistic yield, a part of the N remains unutilized and may be lost.
- High yield levels are rarely reached on the basis of own practical experience alone. A common mistake is make insufficient use of available diagnostic techniques.
- Ensure a balanced supply of nutrients taking into account available soil nutrients. A common mistake is the overapplication or underapplication of some nutrients, e.g. part of NPK remains ineffective where there is S or Zn deficiency, and part of N remains unused where there is P deficiency.
- Check whether nutrients other than NPK, such as Mg, S and micronutrients, should be applied to a crop with high requirements. A common mistake is to overlook hidden hunger, which can limit growth and yield.
- Select the right kind of fertilizer material. A common mistake is the failure to consider the secondary effects of fertilizers, e.g. the S component for increasing the oil content in oil crops and protein content in legumes. In addition, acid-forming fertilizers can be used in high pH soils to bring the pH towards optimum and help in mobilizing deficient nutrients such as Mn and Zn.

- Use fertilizers with a low cost per unit of nutrients where they are equally effective. For example, per unit of P, TSP is cheaper than SSP (where S is not a limiting factor) although, TSP is more expensive than SSP on a per-bag basis. A common mistake is to cost fertilizers on a per-tonne or per-bag basis.
- Nutrients that benefit more than one crop through residual effects should be evaluated and costed differently to nutrients that do not leave a significant residual effect. A common mistake is to equate N and P in a similar manner in terms of their agro-economic response.
- Fertilizer use should give maximum net returns with a minimum benefit-cost ratio (BCR) of 2:1 – the higher the ratio, the better. A common mistake is consider only the BCR, disregarding the absolute net return.

The following sections discuss guidelines for nutrient management and application techniques separately for different nutrients and their sources. Chapter 6 has discussed crop recovery of applied nutrients. Here, after a discussion on the management of individual nutrients, guidelines are provided for the application and management of different sources of nutrients (fertilizers, organic manures, and biofertilizers).

GUIDELINES FOR NUTRIENT MANAGEMENT THROUGH FERTILIZERS

Nitrogen

N is a key nutrient in crop production. The action of N fertilizers on crop growth and yields is a summation of the efficiency with which it is utilized for crop production in terms of yield and quality. Because the correct use of N fertilizer is of great importance from both a production and environmental standpoint, important guidelines for efficient N use are provided here.

Selection and effect of different forms of N in fertilizers

For most crops, the N form (NH_4^+ or NO_3^-) is of minor importance although some plants appear to have a specific preference for one or the other. It might be expected that plants would prefer ammonium as it is directly usable for protein synthesis whereas nitrate must first be reduced to ammonium, which requires energy. For practical purposes, the two major N forms can be considered as largely equally effective. However, in view of its side-effect as a soil acidifier, ammonium is slightly superior in neutral soils where there are no gaseous losses of ammonia. The inferiority of nitrate in paddy rice is because of losses through leaching and denitrification. Nitrate can have an edge under moisture stress such as in dryland farming owing to its greater mobility.

A general shortcoming of most N fertilizers is their high solubility in the soil and rapid action compared with the much slower growth rate of crops. The practical solution to this lack of synchrony is repeated N application through splits during the growth season. Differences in the rate at which N is released play an important role in the selection of N fertilizers for soil application. Nitrate is effective immediately and free in the soil solution. Ammonium acts moderately quickly as, after exchange from charged surfaces, it can be taken up by the roots

and, within a short time, soil bacteria can also transform it into nitrate. Urea acts somewhat more slowly because of the decomposition required to convert its amide form to ammonium, which is a temperature-sensitive process. Slow-release N fertilizers have a very slow and sustained action, which is useful for turf grasses, intensive gardening, greenhouses, high-value crops and for situations involving high N losses and environmental concerns, e.g. sandy soils, high-rainfall areas. Controlled-release N fertilizers, somewhat similar in action, employ techniques such as creating physical barriers through coating easily soluble granules with polymer films, resins, molten S, gypsum, and lac.

For most crops and cropping systems, the N form is of minor importance under good conditions of nutrient transformation and uptake in the soil. This means that the farmer can generally use the cheapest form of N. However, there are important exceptions. Under cold conditions in early spring, quick-acting nitrate fertilizers are superior to ammonium or urea fertilizers unless there is sufficient available soil N to meet the initial needs of the crop. With high temperatures, even urea is sufficiently quick acting except under dry conditions. In the case of acute N deficiency in growing crops, an instant supply of N is required. In such situations, the best option is foliar spraying with urea or N solutions, or top-dressing with nitrate. Under conditions favouring denitrification, as in rice fields, only ammonium or urea fertilizers should be used. In S-deficient fields, ammonium sulphate would in general be superior to S-free N carriers.

Rate of fertilizer N

The amounts of N to be applied depend on the difference between crop requirements and the supply of available soil N, which depends on mineralization of organic matter and residual N from the previous application. The rate of N is also modified by the inclusion of a legume in the system, and by the purpose for which the legume is grown (as a green manure, as an intercrop or as a grain legume in sequence cropping). Sometimes, a grain legume is raised for harvesting the green pods and its residues are ploughed in, which also contributes to the total N supply. Where insufficient N is applied, the expected yield will not be obtained. Where too much is applied, this will decrease the N-utilization rate, increase the danger of lodging in small cereals and lower the disease resistance of crops. Consequently, especially for intensive cropping, reliable diagnostic procedures are very helpful for supplementing the farmer's own experience. Towards this end, the LCC is finding acceptance as a guide to N applications for rice, maize and some other crops.

Timing of N application

Crops need a continuous supply of available N for high yields, especially during the rapid vegetative growth period. For the supply to be adequate before the periods of peak requirement, N fertilizer should be applied in good time in order to avoid even a temporary deficiency. Where a large single application is made to young plants before or at sowing time, this avoids any deficiency during the

early growth stages. However, it may lead to initial oversupply with N lowering plant resistance to diseases, favouring early lodging, causing higher losses during wet periods, and often resulting in a short supply at the yield formation stage. Moreover, the total N requirement of the crop is difficult to assess with only one pre-plant N application. This approach can be used for fertilizing a dryland crop raised primarily on stored soil moisture.

When part of the total N is applied to young plants at the beginning followed by one or two supplementary N applications according to requirements, it results in higher distribution and labour costs. However, the N reserves of the soil are better utilized, transient deficiencies are avoided, and fertilization can be better adjusted to crop needs. The number of portions (splits) in which the total amount of N is to be applied depends on several factors, such as:

- type of crop and its duration;
- total N to be applied;
- soil texture;
- water availability;
- likely outbreak of pests and diseases;
- availability of labour;
- weather conditions.

Depending on the climate, soil moisture status and labour availability, the proportion of total N applied before sowing may range from a small starter dose to the full dose of N. As a general guideline, for irrigated cereals, not more than 30–40 kg/ha should be given at a time. For late N supplies intended to increase grain protein, foliar spraying with urea has proved effective in many situations. Under severe climate conditions, unusual application strategies may be required, such as the application of ammonia-N before winter for the following summer crop in order to facilitate early planting.

Method of N application

Fertilizers applied on the soil surface should reach the main rooting zone without delay and losses. On moist soils or areas receiving frequent rainfall, this is the case with most N fertilizers as they are all water soluble. However, top-dressed fertilizer granules of urea or ammonium-N may remain on the surface during dry periods and lose N as ammonia where exposed to sunshine on neutral to alkaline soils. Fertilizers such as anhydrous ammonia are injected at a certain depth in the soil with special equipment and precautions. For most crops, it is not necessary to place N fertilizers into the rootzone, the exception being crops raised on stored soil moisture. Deep placement of large USGs in the reduced zone of flooded-rice soils is an N-conserving technology that contributes to more efficient N use. Application methods such as foliar spraying or fertigation are covered in a later section.

Minimizing N losses

The purpose of efficient and profitable N application is to obtain a high utilization rate of the applied fertilizer nutrients by the crop in the first year

itself by maximizing N uptake and minimizing losses. Losses of N are not only wasted fertilizer costs – they also have unwanted pollution effects. Losses can be kept below a tolerable level through appropriate crop–soil–water–nutrient management. Farmers tend to tolerate higher N losses where fertilizers are cheap or subsidized, which is not desirable.

Losses of N can potentially be reduced and N utilization by the crop increased by treating urea or ammonium-containing fertilizers with a nitrification inhibitor that delays the conversion of ammonium into nitrate, thus releasing less nitrate for leaching and/or denitrification. The first nitrification inhibitor was an organic compound called N-Serve [2-chloro-6(trichloromethyl)pyridine]. Generally, nitrification inhibitors have not proved successful under field conditions for large-scale application. However, favourable results under field conditions have been obtained in India by treating urea with the oil obtained from the seeds of the neem tree (*Azadirachta indica*), which have been shown to possess nitrification-inhibiting properties.

Secondary effects of N fertilizers

In addition to the direct effect of N as a nutrient, the influence of its positive and negative secondary effects should be taken into account. The main secondary effects are: the supply of other nutrients with the N, such as S, Mg, Ca and B; salt damage of young plants following the application of N close to the seedlings; damaging effects of minor constituents of urea, such as biuret during foliar spray; and the herbicidal or fungicidal effects resulting through application of fertilizers such as calcium cyanamide. The application of N fertilizers can bring about changes in soil reaction with associated nutritional effects. The conversion of ammonium into nitrate creates acidity because nitrification is an acid-forming process. At an assumed utilization rate of 50 percent N, the loss of Ca from the system owing to the application of various N sources would be: 0.4 kg CaO/kg N through CAN; 1 kg CaO/kg N through urea; and 3 kg CaO/kg N through AS. However, there can be a gain of 1 kg CaO/kg N through calcium nitrate application.

Strong soil acidification as a result of N fertilizer application is a disadvantage in acid soils because this acidity must be compensated for by liming in order to maintain an optimal pH range for better nutrient availability and microbial activity. However, in intensive agriculture on high pH soils, the acidifying effect of N fertilizers may result in additional mobilization of nutrients such as Fe, Mn and Zn. This short-term acidification contributes towards a more balanced nutrient supply. Acidification of alkaline soils may be advantageous because it increases P supply by making calcium phosphate more soluble and also increases micronutrient availability.

Phosphorus

Selection of the appropriate P fertilizer

The choice of P fertilizer to be used depends on several soil factors, climate conditions, crop characteristics, economics and secondary effects of fertilizers.

In spite of numerous comparative studies made worldwide, no universally applicable advice can be given. However, some suggestions may be helpful. Water-soluble P fertilizers are best on slightly acid to neutral and alkaline P-deficient soils, particularly for short-duration crops with an immediate need of available phosphate. However, a high degree of water solubility can be a disadvantage in soils with strong P sorption where phosphate ions are transformed rapidly into less available forms. Phosphate forms with only moderate water solubility give the best results on moderate to slightly acid soils.

Slow-acting PRs require sufficient amounts of soil acidity and biological activity for conversion into easily available P forms. Their special advantage is their lower cost and a lower solubility, which decreases the rate at which the P is adsorbed in soils rich in active Fe or Al compounds. The use of very slowly acting PR is restricted to strongly acid soils and on perennial crops such as rubber, tea, and oil-palm. Thus, depending on the soil and crop situation, P fertilizers ranging from fully water soluble to zero water solubility can be utilized effectively.

The form of P is much more important on P-deficient soils than on those well supplied with P. The relative importance of higher water solubility decreases as the soil P status improves and the crop duration increases. Therefore, from a practical point of view, for cropping systems that have received an optimal supply of P for some years and P is needed mainly for the maintenance of an adequate P level, both the quick and somewhat slower-acting P forms can be equally effective. In spite of what is known about the effectiveness of various P sources, many farmers tend to buy the cheapest P source based on the price per unit of P_2O_5 and, sometimes, erroneously, even on the basis of price per bag. They should, for example, not be tempted to buy "cheaper" PR if it will not be effective under their conditions.

Rate of P application

This important aspect has been discussed together with diagnostic methods in Chapter 4. The general guideline is to decide the optimal rate of P based on soil fertility levels, response rates and the cost of P. There are two strategies for deciding the P application rate. First, on P-deficient or strongly P-sorbing soils, sufficient P is applied to meet the plant demand for low and medium yield levels. The second strategy is to raise the P level of the soil up to the optimal range and maintain it there by adding sufficient P to replace the P removed by the crops, a concept that has proved effective in sustaining high yields. Farmers can select the strategy based on whether they are interested in short-term response or long-term soil fertility buildup as well. The resources required for adopting the buildup plus maintenance approach are also an important aspect in decision-making.

Timing of P application

In order to make the best use of a P fertilizer, it should be applied according to its properties. Water-soluble forms must be applied at or before sowing time into the rootzone with as little as possible soil contact (granulated products or "placed" near the roots); top-dressing afterwards will have a delayed effect because of slow

penetration into the soil. However, on P-deficient soils, a delayed application (up to one month after sowing) is better than no application at all, particularly where the desired P fertilizer is not available in the market in time. Phosphate fertilizers, such as powdered PR, that must be solubilized in the soil before they can furnish P for crop use, should be applied 3–4 weeks before sowing and well mixed into the topsoil in warm areas. For seasonal crops, incorporation of PR up to 10–15 cm depth following broadcast has been suggested (FAO, 2004a 2004b). Application in autumn is advisable for summer crops in temperate areas.

Methods of P application

The solubility and availability of soluble P fertilizer is better protected where there is restricted contact between soil and fertilizer. This happens where the fertilizer is concentrated locally in small zones near plant roots rather than being distributed evenly within the whole field. Minimizing soil contact means less and slower conversion into moderately available soil-P forms. Placement can improve the utilization of water-soluble P fertilizers by up to 25 percent in the first year, with the residual effect being hardly affected. In contrast, the best approach for insoluble fertilizers such as PRs is to maximize the soil fertilizer contact by spreading and mixing them with the whole topsoil.

Placement increases P uptake especially under: (i) low P supplies in the soil; (ii) dry periods or years; (iii) wide spacing of plants (e.g. maize); (iv) low rates of P application; and (v) plants with short vegetative growth periods (by enabling a rapid start of initial root growth). In contrast, the special efforts and costs of placement are hardly worthwhile with narrow-row crops in soils with good moisture conditions in humid regions. Special machinery can be used to place fertilizer around the seed (contact fertilization), alongside the seed (row fertilization) or underneath the seed (strip fertilization). Where specialized machinery is not available, placement can be achieved by ploughing and applying the fertilizer under the seed row before sowing.

Utilization of P fertilizers

Compared with N and K fertilizers, the recovery rate of P fertilizers by crops is low. About 15 percent of the P added is utilized during the first year, the range being 10–25 percent. The utilization of P by subsequent crops continues through residual effects, which may continue for a long time, reaching a rate of about 50 percent within 20–30 years. However, for economic reasons, only the residual effects of a few years can be considered (Chapters 6 and 9). For a better utilization rate of applied P, the fertilizer should be given directly to the most responsive crop in the rotation. For example, in rice–wheat or maize–wheat rotation, the best direct plus residual responses are obtained where P fertilizer is applied to wheat while the succeeding crop of rice or maize is allowed to feed on soil reserves and residual P. This is also because wheat is a winter-season crop and benefits more from direct P application as the low temperatures are not very favourable for adequate release of soil P.

In contrast to N, phosphate is rarely leached out of the soil. This is the primary reason why residual effects of P are more important than those of N. Where leaching does occur, the amounts are generally less than 1 kg P/ha and insignificant from a pollution point of view.

Secondary effects of P fertilizers

The selection of P fertilizers is not only a matter of the P form, it must also consider secondary effects. Some phosphate fertilizers also supply S, Mg, Mn and Si, while others have an enhanced soil-structure-improving capacity. Some P fertilizers decrease and others increase soil reaction, and some are superior in immobilizing harmful substances. For example, where SSP gives better yields of crops than does TSP, this may be because of the S supplied through SSP. Where Thomas phosphate (basic slag) is superior to SSP, this may be because of the additional liming effect or Mg supply.

Potassium

Selection of K fertilizer

The selection of K fertilizers is relatively simple compared with that of N and P fertilizers. All soluble K fertilizers are more or less similar with respect to their K-use efficiency. The main choice is between potassium chloride and potassium sulphate. For plants that are tolerant to chloride and whose quality is not impaired by high Cl, the cheaper potassium chloride (MOP) is preferred. For plants that are sensitive to high Cl for quality or other reasons, potassium sulphate or potassium nitrate is a better choice. Of the agricultural crops, potatoes and tobacco and many horticultural crops belong to the chloride-sensitive group. However, the Cl component is suitable for "salt-loving" plants, such as sugar beets and palms, and it brings extra beneficial effects. The K component of NPK complexes is similar to the K in straight fertilizers.

Timing and method of K application

It is a standard practice to apply the total amount of K just before sowing or planting by mixing it into the top layer. It is placed when the NPK complexes are drilled. At later growth stages, top-dressing on the soil surface is also effective. Where very high amounts are required, there may be some salt damage to young plant roots during dry periods. In order to avoid this, split applications are preferable. Split application of K together with N can be a useful strategy where leaching losses of K are considerable (as in sandy soils under high rainfall). Losses through leaching occur mainly in periods of high water penetration on sandy or peat soils with a low storage capacity. Placement of K is advisable in cases of single plant fertilization, e.g. trees and tea bushes. On most production sites, K losses are insignificant from both an agricultural and an environmental viewpoint.

Secondary effects of K fertilizers

Several K fertilizers also provide other nutrients that can have a beneficial effect on crop yields and produce quality, excluding Cl. Potassium sulphate also contains S, which can be useful on S-deficient soils and for high S-demanding crops. For crops with a high Mg requirement or on Mg-deficient soils, fertilizers with a combination of K and Mg are recommended, potatoes being a typical example. In such situations, potassium magnesium sulphate can be used. Potassium nitrate also provides readily available N and is a preferred source for several horticultural crops. The chloride component of MOP is particularly useful in the nutrition of sugar beets and palms. On grassland, the Na in K fertilizers can be of benefit to grazing animals. In some countries, Na is considered an impurity and a maximum permissible limit is set.

Sulphur

S can be applied to the soil through any suitable S carrier. The choice depends on: crop, local availability, price and the need for other nutrients. All sulphate sources are generally equally effective as they contain S in the water-soluble, readily available sulphate form. S is applied automatically where sources such as AS, SSP or APS are used to provide N, P or N + P. Rates of S application generally range from 20 to 50 kg S/ha depending on the S status of soil and crop demand. Higher rates are generally needed on sandy soils and for oilseed crops. In most cases, S is applied at or before sowing along with N, P, K or Zn when two nutrient fertilizers are used. Where sulphate salts of micronutrients are used to correct specific micronutrient deficiencies through soil application, the S added through them should be taken into account in deciding the total rate of S to be applied. However, such materials cannot be selected to supply S where their micronutrients are not required.

Where elemental S or pyrites are used, these should be applied 3–4 weeks ahead of planting through surface broadcast on a moist soil followed by mixing. This allows sufficient time for the insoluble S in them to be converted to the plant available sulphate form. The rate of oxidation of elemental S is controlled by: the particle size of the material; temperature; moisture; and the degree of contact with the soil. S in materials of finer particle size oxidizes at a rapid rate. Where S deficiency is noticed in a growing crop, this can be corrected by providing a top-dressing with ammonium sulphate, or a suitable liquid S fertilizer can be given as foliar spray. Where the S application rates are medium to high, a significant residual effect can be expected.

Calcium

Several Ca fertilizers have been described in Chapter 5. Specific fertilization with Ca is not often needed as most soils have a satisfactory status of available Ca. Significant amounts of Ca are applied where acid soils are limed with calcium carbonate or with dolomite. Ca is also delivered wherever gypsum is applied as an

amendment or as a source of S, and where N is provided through CAN. In many areas, gypsum application to groundnut is specifically recommended in order to meet the high demand for Ca during pod formation. It should be applied in furrows.

The rate of Ca application may vary from zero for cereals on calcareous soils to 500 kg Ca/ha for bananas under humid tropical conditions. To correct Ca deficiency in standing crops, foliar sprays with water-soluble materials such as calcium chloride or preferably calcium nitrate can be given. In many apple-growing areas, e.g. in South Africa, it is common to use CaCl_2 sprays (0.5 percent) or calcium nitrate (0.65 percent) at 40–45 days after flowering to avoid the occurrence of “bitter pit” (FAO, 1992).

Magnesium

Mg application is more widely recommended than that of Ca. Fertilizers containing Mg have been described in Chapter 5. Sufficient Mg is added where acid soils are limed using dolomitic limestone. Most fertilizers containing magnesium sulphate are equally effective as sources of Mg. In very acid soils, especially under plantation crops, the mineral magnesite can also be used to apply Mg. For cereal crops on acid soils, the rate of Mg application can range from 10 to 50 kg Mg/ha depending on the Mg status of the soil and crop needs. Higher rates of 30–120 kg Mg/ha are recommended for grasslands in order to avoid grass tetany in animals. For high-yielding crops in the tropics, some recommended rates are (in kilograms of Mg per hectare): pigeon pea 18; rice, cotton and coffee 20; cassava, maize, potatoes and pineapple 30; yams 34; sugar cane 35; and bananas 50 (FAO, 1992).

Mg fertilizers can be applied to the soil or given as foliar spray. The readily water-soluble Epsom salts ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$), magnesium chloride and magnesium nitrate are used as foliar sprays either to prevent losses in yield and quality caused by acute Mg deficiency or as part of the regular fertilizer schedule.

Boron

Common sources of B have been described in Chapter 5. Most B fertilizers are soluble borates. Various borates differ in their B content depending on the amount of water in their structure. Slow-release boron frits have a longer-lasting effect than soluble sources. They are particularly suited for sandy soils and high-rainfall areas to reduce leaching losses of B. Because of the small quantities involved and in order to ensure uniform application, B is sometimes applied through boronated fertilizers. A wide range of boronated fertilizers are produced around the world.

In order to avoid any chance of toxicity, B should be applied only where its deficiency has been confirmed. The recommended rates on B-deficient soils for most crops range from 0.5 to 2 kg B/ha. Higher rates of 2–6 kg B/ha are indicated for almonds, grapes and walnuts (Shorrocks, 1984). B can be applied to the soil or through foliar spray. Soil application is generally given before sowing. Higher rates of B application are more appropriate for broadcast application, whereas lower rates would be more suitable for side-dressing. In all cases, direct contact

of the fertilizer with the seed should be avoided. The concentration of B in spray solution can range from 0.1 to 0.5 percent but should be decided on the basis of local conditions.

The application of B fertilizers poses more problems than other micronutrients because of the highly different requirements of crops in a rotation. Crops with a high demand should be well supplied with B especially for high yields but not excessively, because a following crop that has a low B requirement may be damaged instead of being nourished by residual B.

Chlorine

Chloride is rarely applied deliberately although it is delivered wherever chloride-containing fertilizers such as MOP, calcium chloride and MOP based NPK complexes are used. It is a nutrient to be kept in mind where fertilizing palms on sandy soils or sites away from the sea. Practical recommendations for the application of chloride to coconut and oil-palm are available (IFA, 1992). For coconuts under Malaysian conditions, the rate of application ranges from 0.11 kg Cl/tree at an age of 6 months and increasing progressively to 0.9 kg Cl/tree. Oil-palms are considered to be deficient in Cl where their leaves contain less than 0.25 percent Cl in the dry matter.

Copper

Cu can be applied through a variety of inorganic salts and chelates. These have been discussed in Chapter 5. Cu application should normally be based on the available-Cu status of soils. Both soil applications and foliar sprays are suitable. A single pre-plant soil application can be effective for several crops grown in succession, and each crop need not receive Cu fertilizer except on organic soils. For soil application, the rates of Cu applied vary widely from 1 to 23 kg Cu/ha (Shorrocks and Alloway, 1988). Normally, recommended rates are 1.5–4.5 kg Cu/ha where banded, and 3–6 kg Cu/ha where broadcast (FAO, 1983).

Because Cu is complexed strongly by SOM, the amount applied (5–10 kg Cu/ha) is high compared with plant requirements. A single application is sufficient for several crops. Application rates are lower on sandy soils or those with a low organic matter content. Cu fertilizers leave a significant residual effect on the following crops, hence, there is no need for annual applications. Cu fertilizers should be well mixed with the topsoil. On grassland, they penetrate only slowly into the soil.

The commonly advocated concentration for spray application is about 0.025 percent Cu (100 g Cu/ha as copper sulphate, equivalent to 400 g CuSO₄.5H₂O). However, some specialists do not advocate the use of copper sulphate for foliar spray because it can be phytotoxic even at low concentration and can also corrode the spraying equipment (Shorrocks and Alloway, 1988). To save on application costs, foliar sprays of Cu can be carried out using chelates and oxychloride of copper, which are compatible with many agrochemicals and can, therefore, be applied with a fungicide or a herbicide. Spray application has the

advantage of delivering Cu directly to the plant, which is not the case with soil application if Cu is strongly adsorbed in unavailable forms. In some cases, dusting of maize seed with copper sulphate or soaking of oat and vetch seed in 1-percent solution of copper sulphate has also been found to be effective.

Iron

Iron chlorosis is considered to be one of the most difficult micronutrient deficiencies to correct in the field (Tisdale, Nelson and Beaton, 1985). A number of Fe fertilizers have been described in Chapter 5. The most common fertilizer for soil application is ferrous sulphate. However, the soil application option is generally not preferred owing to the rapid oxidation and immobilization of the ferrous to ferric iron in the soil. Rates of ferrous sulphate applied to the soil range from 20 to 100 kg/ha of $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ (19 percent Fe). The efficacy of soil-applied ferrous sulphate improves where it is mixed with an organic manure and applied.

The commonly recommended method of Fe application is through foliar sprays either as inorganic salts or preferably through chelates of Fe with EDTA, EDDHA, etc. The Fe-EDTA chelate is useful only in slightly acid soil while Fe-EDDHA is unique as its stability remains constant over a wide pH range of 4–9. Where ferrous sulphate is used for foliar spray, its concentration ranges from 0.5 to 2 percent. The sprays have to be repeated several times at 10–15-day intervals. In calcareous soils, Fe availability can be increased by using acidifying materials such as elemental S wherever its use is economic.

Manganese

A number of Mn fertilizers are available (Chapter 5). As with Fe, foliar application of Mn is generally more effective than its soil application. For soil application, manganese sulphate is a superior source of Mn compared with other sources. However, soil application is generally uneconomic owing to the conversion of applied Mn into insoluble forms. In spite of being only slightly water soluble, manganese oxide can be a satisfactory source of Mn. It must be finely ground in order to be effective. Mn deficiency induced by liming or high pH can be corrected by soil acidification, e.g. by the use of elemental S or by applying Mn fertilizer along with AS.

The rate of Mn application varies from 1 to 25 kg/ha. The lowest rates are for foliar spray and the highest rates pertain to soil application by surface broadcast. When Mn fertilizer is banded, usually half the rates for broadcast application are needed. For foliar application, Mn can be applied either through a 0.5–1.0-percent solution of MnSO_4 or through a suitable chelated compound. For wheat in Mn-deficient soil, the recommendation is to give one spraying of 0.5-percent MnSO_4 solution (at a per-hectare rate of 2.5 kg MnSO_4 in 500 litres of water) 2–4 days before irrigation followed by 2–3 additional sprays at weekly intervals on sunny days. The natural organic complexes and chelates of Mn are best suited for spray application.

An alternative to adding Mn to the soil is to improve Mn availability by: using acidifying-N fertilizers such as AS; compacting loose soils; and preventing excessive soil drying. All of these measures favour reducing conditions that produce plant available Mn^{2+} ions. However, such practices may reduce the availability of other nutrients.

Molybdenum

Mo is required by crops in the smallest amounts of all micronutrients. A number of fertilizers containing Mo have been described in Chapter 5. Rates of Mo application are generally very low, ranging from 25 to 150 g Mo/ha. It can be applied to the soil, given through foliar spray or through seed treatment. The optimal rate of Mo depends primarily on the soil, the crop and the method of application. In order to obtain satisfactory distribution of the small amount Mo applied to soil, Mo fertilizers are sometimes combined with multinutrient fertilizers. For example, in Australia, MoO_3 is incorporated into PR pellets (Tisdale, Nelson and Beaton, 1985). Mo can also be applied through SSP fortified with 0.05 percent Mo. In the case of strongly acid soils, the amounts need to be doubled. Mo can also be applied to the seed, to the nurseries or by soaking seeds in a solution of Mo fertilizer. Mo fertilizer may not be required where the soil supply is improved by liming, loosening and better drainage.

Zinc

Among micronutrients, Zn deficiency is perhaps the most widespread. Zn can be applied through a number of inorganic and chelated compounds (discussed in Chapter 5). Zinc sulphate is the most commonly used source of Zn. Soil application rates of Zn are typically in the range 4.5–34 kg Zn/ha in the form of zinc sulphate (broadcast or sprayed in an aqueous solution onto the seed bed). Higher application rates are often used for sensitive crops, such as maize, on alkaline and/or calcareous soils as opposed to maize on non-calcareous soils (Alloway, 2004). In India, where Zn deficiency is a widespread problem, soil application of 5 kg Zn/ha is advised on coarse-textured soils, and 10 kg Zn/ha on fine-textured soils. One application can last for 3–6 crops.

In the rice–wheat rotation, where Zn availability is low, the application of Zn to rice is more profitable. In Brazil, 5–7 kg Zn/ha through zinc sulphate is generally used to correct Zn deficiency in both lowland (paddy) and upland rice. The amount of Zn required to be applied to a wetland rice soil depends on soil characteristics, source of Zn, severity of Zn deficiency, and variety of rice to be grown. Generally, 10 kg Zn/ha as zinc sulphate or root dipping in 2-percent zinc oxide is adequate for most situations (Neue and Mamaril, 1985). Application of Zn to the floodwater or to the soil surface has been found to be more efficient than its incorporation into the wetland soil.

As with most crops, the normal way of correcting Zn deficiency in wheat soils is to surface broadcast a Zn compound, usually zinc sulphate at 5–20 kg Zn/ha to the seed bed and incorporate into the topsoil. Where the Zn fertilizer is to

be banded (placed to one side and below the seed in the row), then a lower rate of 3–5 kg Zn/ha is used. For foliar applications (usually of a chelate such as Zn-EDTA), an even lower rate of 0.015–0.25 kg Zn/ha is used. In order to correct Zn deficiency in a standing crop, the crop can be sprayed with a 0.5-percent solution of zinc sulphate (0.5 kg of zinc sulphate in 100 litres of water). Before spraying, 250 g of unslaked lime (0.25 percent) should be added to the solution in order to neutralize the acidity of the zinc sulphate (Gupta, 1995).

Because of the small amount of Zn required, special procedures have been developed, e.g. dipping roots into zinc oxide slurry/paste, and hammering a zinc nail into a Zn-deficient tree so that the sap may dissolve some of the Zn and take it up. Other alternatives include dipping the roots of rice seedlings in a 1-percent zinc oxide suspension before transplanting or mixing zinc oxide with pre-soaked rice seeds before direct seeding. Dipping potato seed tubers in 2-percent zinc oxide suspension is also effective. The high seed rate (3.0 tonnes/ha) of potato makes it possible to supply the micronutrient needs of potato through soaking.

GUIDELINES FOR FERTILIZER APPLICATION

Basic aspects of fertilizer application

Recommendations for the application of nutrients are generally made on a nutrient basis (Chapter 8). However, these are never applied as nutrients but in the form of specific products such as fertilizers and manures. Various sources of plant nutrients have been described in Chapter 5. The method of application of fertilizers and other nutrient sources is a very important aspect of nutrient management. At the field level, this also means fertilizer management. Fertilizers containing the same nutrient differ markedly not only in their chemical properties and nutrient content but also in their physical characteristics. All of these determine the method of fertilizer application. The crop, soil and available equipment and labour are equally important.

The objective is to apply a fertilizer in such a way that the nutrients in it contribute as much as possible towards crop production. This can be accomplished by ensuring that fertilizers remain in the active rootzone, improve the soil fertility and produce minimum negative effects on the environment. A prerequisite of correct fertilizer application is its uniform distribution over all the treated area whether it is surface broadcast or applied in a restricted manner. The method of application should follow the research findings about the most suitable technique for a given soil and crop situation. The following section deals primarily with solid fertilizers. The methods of fertilizer application in general have also been described in FAO/IFA (2000). Liquid materials are discussed in a later section. Guidelines for the application of organic manures and biofertilizers follow this section on mineral fertilizers.

Multinutrient fertilizers vs single-nutrient fertilizers

Farmers want fertilization to be effective, simple and cheap. This can be achieved through the use of straight fertilizers or suitable complexes. In the case of straight

(single-nutrient) fertilizers, a separate fertilizer has to be purchased for each nutrient to be applied (urea for N, TSP for P, MOP for K, $ZnSO_4$ for Zn, etc). Where a suitable multinutrient product is available in which the ratio of nutrients is close to or similar to the ratio of nutrients recommended, then one fertilizer can do the job. For example, where agronomically suitable, a 15–15–15 complex can provide any amount of NPK if these are to be applied in a 1:1:1 ratio, or a product of the grade 20–20–0 can deliver N and P if recommended in equal (1:1) amounts.

For SSNM, a multinutrient fertilizer that matches the exact nutrient needs of a field is very often not available. In such cases, either separate single-nutrient fertilizers are selected or a tailor-made mixture or bulk blend is prepared. In many situations, a suitable multinutrient fertilizer can be selected for the basal dressing followed by a straight fertilizer for top-dressing.

Both approaches of whether to prefer single-nutrient carriers or multinutrient products have their advantages and drawbacks. The use of single-nutrient fertilizers often provides flexibility, lower cost per unit of nutrient and the advantage of applying only those nutrients that are needed and will generate an economic benefit. However, this approach involves purchasing, handling and applying several materials and possibly making mistakes in computing the quantities of fertilizers required to deliver the desired nutrient rates. Mistakes can also occur while mixing different fertilizers not only in terms of quantities but also in terms of compatibility.

Multinutrient fertilizers have their special advantages, especially with bulk blending and on-farm mixing. Of the economic arguments, the difference in price per nutrient unit is often decisive. Where single-nutrient fertilizers can be obtained more cheaply, there is a strong incentive to use them and either to distribute them separately, mix them on the farm before application or to make use of cost-effective bulk-blending facilities. Where the farmers are not adequately trained but their soils need the application of several nutrients, they should apply a suitable multinutrient fertilizer rather than deciding and purchasing separate fertilizers for each nutrient needed. Chapter 5 includes some guidelines for the handling, storage and mixing of fertilizers.

In view of the multitude of soils and cropping systems under cultivation, only a few suggestions can be provided here for the application of multinutrient fertilizers. In general, the grade to be selected should come closest to delivering the nutrients in the ratio recommended for the crop. Otherwise, a suitable combination can be sought. For example, application of 40 kg each of N, P_2O_5 and K_2O can be made by: (i) selecting separate fertilizers for each nutrient; (ii) a 1:1 N: P_2O_5 complex plus a straight K source; and (iii) a 1:1:1 N: P_2O_5 : K_2O complex or blend.

As N is the component most liable to loss, these fertilizers must be applied with an eye on high nitrogen-use efficiency. PK fertilizers or NPK types with little N are very useful for providing a good initial supply allowing N to be applied later according to the special crop needs. Special soil nutrient supplies will also influence the choice of fertilizers. On a soil especially rich in available K, NP

fertilizers will be the choice, whereas NK fertilizers are the right choice on soils rich in phosphate. Most multinutrient fertilizers have an acidifying influence on the soil reaction, similar to N fertilizers.

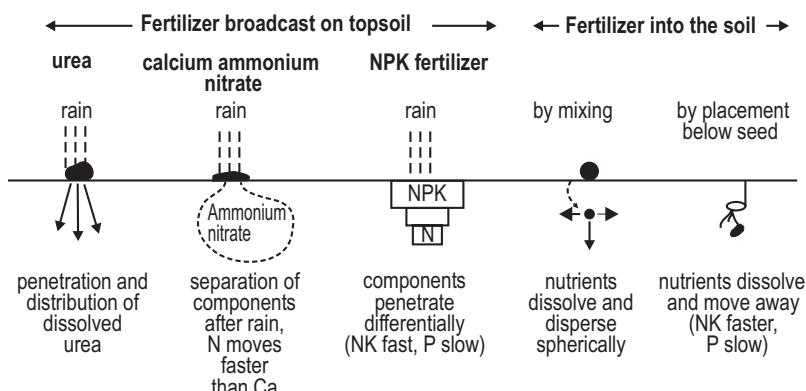
The choice between solid, liquid and gaseous fertilizers depends on factors such as economics, efficiency and ease of operation, and on whether fertilization and crop protection can be partly combined. These can generally be evaluated according to farm-specific conditions.

Size of fertilizer particles

Theoretically, fine, powdery material mixed thoroughly into the topsoil layer would result in the most uniform distribution within the rootzone. However, this is not always so and it is often too costly. The use of granular, water-soluble fertilizers represents a compromise between uniformity of distribution and ease of application. The granule size of water-soluble fertilizers is generally standardized so that 90 percent of the granules are 2–4 mm in diameter. Large granules have the advantage of a reduced immobilization, which is especially important for phosphates. Very large supergranules of 1–2 g are sometimes used for placement in rice and for trees.

Because water-insoluble fertilizer granules would release nutrients too slowly, they are granulated in such a way that powdery material is only bound loosely. Thus, in moist soils, the granules disintegrate rapidly. In all cases, the granules must be sufficiently stable to withstand transportation and spreading. When the granulated fertilizer disintegrates into powder in the soil, it should have close contact with soil particles in order to achieve the necessary mobilization (Figure 38).

FIGURE 38
Penetration and incorporation of fertilizer nutrients into the rootzone



Source: Finck, 1992.

Fertilizer distribution on the soil surface

The application of granulated fertilizers on the soil surface is the easiest and most common procedure. The fertilizer granules should be distributed as uniformly as possible in order to supply each plant with nutrients in more or less equal amounts. This is not an easy task. Experienced farmers are able to spread fertilizers by hand with considerable accuracy but mechanical distribution is superior in most cases. The difficulty of hand spreading uniformly 120 kg N/ha through a standard NPK fertilizer requires the distribution of 24 million granules per hectare (2 400 granules/m²).

Non-uniform fertilizer distribution is a sign of faulty application. It results in some plants receiving too little or too much nutrient within the same field. The deviation from uniformity should not exceed 10 percent. The principle of homogeneous distribution on the whole field has its limitations where the soil in the field has variable nutrient status. In such cases, precision fertilization is required (discussed below).

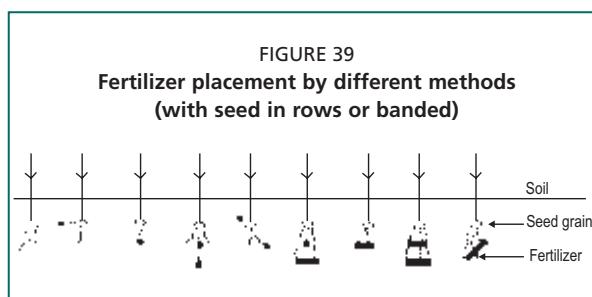
Penetration of surface-applied nutrients into the rootzone

Fertilizers spread on the soil surface, whether bare soil or with plant cover, will penetrate slowly into the top layer if they are water soluble and if there is sufficient moisture. Dryness after fertilization results in a delay in fertilizer nutrient uptake because the applied nutrient cannot be transported to the roots owing to inadequate moisture. Water-insoluble fertilizers such as PRs or elemental S products need to be mixed into the rootzone after application on the surface. The incorporation of insoluble fertilizers applied to grassland is generally left to slow mixing by soil fauna. Because this is a slow process, a good supply of nutrients should be given during seed-bed preparation or at sowing.

During the penetration process, fertilizer components of different solubilities in the same product separate. For example, in the case of calcium ammonium nitrate, the CaCO₃ remains on the surface much longer than does the easily soluble ammonium nitrate. Once in the soil, the nitrate moves more quickly than does the ammonium. In the case of an NPK complex fertilizer, the N component moves more quickly than the K and much more quickly than the P (Figure 38).

Placement of fertilizers

Placement usually means positioning the fertilizer in a desired region or depth at sowing, either at the side or below the seed. It is normally done where the entire field is not to be treated or where restricted soil fertilizer contact is desired, as in the case of highly water-soluble but relatively immobile nutrients such as water-soluble phosphates. Placement is also the preferred method of fertilizer application for crops planted in widely spaced furrows, e.g. maize, potato, sorghum, sugar cane and pineapple (except for bushes and tree crops). Fertilizer placement generally results in a better rate of nutrient utilization by the crop and, thus, higher NUE compared with a broadcast application. It is an also effective



Source: Finck, 1992.

method under resource constraints where small rates are to be applied in soils of low to medium fertility.

Where placed beside the growing plants under wide spacing, the fertilizer is termed a side-dressing. Placement is suitable for all nutrients, but best results are obtained with N and phosphate in fields with wide-row crops. The benefit of placement is greatest at

low rates of application and during early growth in periods of dry or cool weather when nutrient uptake is impeded. Its key advantage is that it places the nutrients in the rootzone where they are needed. Its main disadvantage is the higher cost of application.

Placement can be profitable for small cereals in dry areas, but for wheat in humid areas it would hardly justify the extra costs. For micronutrients, placement can take the form of seed treatment, which provides a good initial supply as for example with Mo fertilizers. When roots of rice seedlings or potato seed tubers are dipped or soaked in nutrient solutions before planting, this also results in a kind of placement in the rootzone. Fertilizer placement requires combined sowing and fertilizing machines that place the fertilizer in different ways below or next to the seed (Figure 39).

Fertilizer placement is generally made at sowing time or soon after in a number of ways:

- in a band a few centimetres to the side and below the seed;
- in a band directly below the seed, although this may hinder growth of the tap-root;
- in immediate contact with the seed, termed combine drilling (only in moist soils and mainly with phosphate as close contact with N may damage the seed);
- in one or two bands on one or both sides of plant rows;
- by spot application between plants as in the case of USGs between rice hills or as in the case of ring placement around trees.

Application equipment for solid fertilizers

The main problem with fertilizer application is non-uniform distribution in the field. Compared with the widely used and tedious spreading of fertilizer by hand, mechanical distribution is labour-saving and more precise. However, it should also be cost-effective. Precise and more expensive spreading procedures may be worthwhile for expensive fertilizers used to produce high yields on medium-large farms. The amount of fertilizers to be spread ranges from about 50 kg/ha to more than 1 500 kg/ha. The cost of distribution can range from 10–20 percent of the total fertilizer costs.

The requirements for suitable mechanical distributors are:

- delivery of exact rates;
- uniform distribution of the fertilizer with a deviation of less than 10 percent;
- distribution to be independent of slope and speed;
- ease of handling, operation and maintenance;
- resistance to corrosion;
- energy efficient.

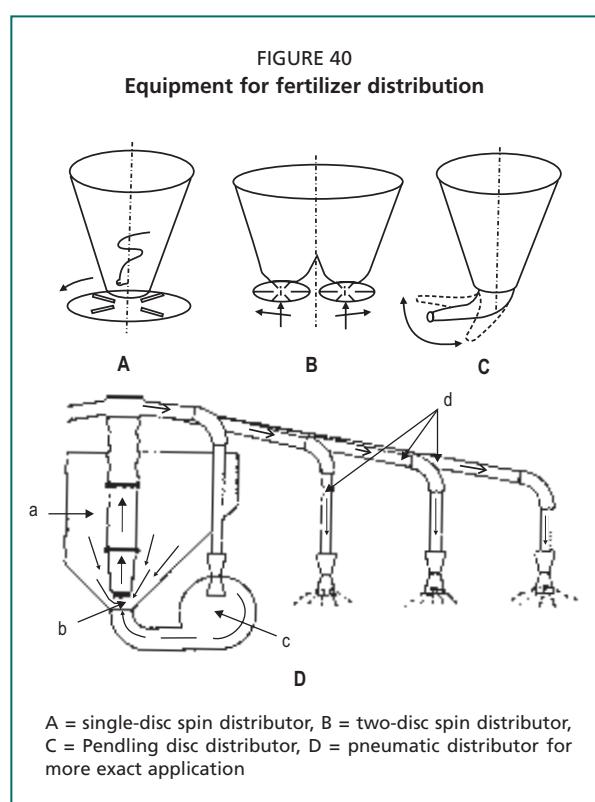
Beyond the simple box-type of distributors, there are ejection distributors and high-precision distributors. They all have their advantages and limitations.

Box distributors

Box distributors with a width of 2–5 m operate with a simple mechanical system of moving chains, rotating plates or a moving lattice. They can be adapted to apply both granular and fine-grained fertilizers. However, they have only a small capacity and can only be operated at slow speed, which limits their use.

Ejection distributors

Ejection distributors (centrifugal spreaders) operate on the principle of ejecting fertilizer granules by using centrifugal force either by spinning discs or by oscillators. The simplest spinning-disc equipment operates with one disc that spreads granular fertilizers with an acceptably uniform distribution. Those with two counter-rotating discs or oscillating-spout distributors provide even better distribution. Such distributors are also suitable for fertilizers with a finer particle size. Spinning-disc types are the most common ones for cheap and relatively uniform fertilizer spreading. The fertilizer is metered from a hopper onto a rapidly spinning disc and flung laterally to a width of about 10 m on each side (Figure 40). They cover wide strips of the field at a reasonable speed and accuracy. About half of the strip receives the full amount of fertilizer whereas



Note: (a) = injector gate, (b) = air blower, (c) = outlet pipes, (d) = delivery points.

Source: Finck, 1992.

towards both ends the amounts decrease. This gradient is compensated for by a system of overlapping in order to obtain full uniformity for the whole strip.

The distributors are either connected to a tractor with a container volume of 300–1 000 litres or have their own container, which can hold up to 4 000 litres. The rate of fertilizer distributed ranges from 50 to 2 000 kg/ha. The accuracy of distribution is usually about ± 10 percent, up to a maximum of ± 20 percent. As medium accuracy suffices for most purposes, broadcasting with simple types of spinning-disc distributors is very common.

High-precision distributors

For more accurate and precise distribution of fertilizers with varying physical characteristics, pneumatic types of distributors are preferable. However, they are much more expensive. In these distributors, the granules are transported through tubes by air pressure and finally blown on small plates about 1 m apart. The result is a semi-circle distribution with good overlap. Such machines cover a width of up to 15 m or more and the container volume ranges from 1 000 to 2 000 litres. They can deliver fertilizer at rates ranging from 30 to 2 000 kg/ha and they are suitable for fertilizers of average granule size, for mixtures and also for small granules and urea prills. They provide a sufficiently uniform distribution.

Aerial application of fertilizers

An increasing amount of fertilizer is distributed by aircraft. However, this method is generally more expensive than other methods. Large areas can be fertilized in a short time, especially at low fertilizer rates. The method is applicable in difficult terrain, be it paddy fields or steep mountain areas. One advantage of aerial application over normal soil application is that the wheels of vehicles cause no soil compaction or damage to crops. However, the method has little practical feasibility for smallholders in developing countries. Aerial application requires careful and precise marking of application areas in order to avoid accidental contamination of open waters. The maintenance and marking of buffer areas around watercourses and water bodies (to avoid drift or accidental application of fertilizers directly to surface water) is mandatory in certain countries. Aerial applications have to be done during favourable atmospheric conditions when the likelihood of significant drift is lowest.

Application of liquid and gaseous fertilizers

Several liquid and gaseous fertilizers have been described in Chapter 5. Some of these require special application techniques while others can be sprayed on the leaves with conventional sprayers.

Application of liquid fertilizers

Liquid fertilizers serve two different purposes, either to supply nutrients to the soil or to provide direct nutrient supply to plants through foliar sprays. Fertilizer solutions provide for better soil transport and distribution of nutrients compared

with granular fertilizers. Suspensions, which are concentrated solutions with small suspended solid particles, usually have higher nutrient concentrations than do liquid solutions. Both require solid and corrosion-resistant tanks or silos for storage and transport, good safety measures and special application equipment. Liquid fertilizers that can be applied on bare soil or on soils covered with plants include: fertilizer solutions, fertilizer suspensions and organic materials such as animal slurry. These can be materials containing one or more nutrients including macronutrients and micronutrients.

Application of liquid fertilizers on bare soils is made through special nozzles spaced about 50 cm apart and operating at pressures of 100–300 kPa that deliver relatively large drops. Being turbid liquids, suspensions require special nozzles that do not become blocked by the small solid particles. Different travel speeds and discharge rates that can be regulated from 0.5 to 4 litres/minute permit the application of 10 to 300 kg N/ha. Position markings are required in order to avoid overlapping. Concentrated solutions or suspensions cause no osmotic problems on bare soils. This is because they enter the topsoil layer through pores and are diluted by the soil moisture.

The application of concentrated fertilizer solutions through a canopy of young plants can cause serious osmotic damage. Therefore, the solution should be diluted 2–3 times with water so that the leaves can tolerate the osmotic stress. An alternative method is to apply through dropper tubes, which deliver the solution on the soil surface under the crop canopy. Driving on well-defined wheel paths is the best guarantee for properly joining the individual fertilizer strips.

Aqueous ammonia may lose ammonia through evaporation. Therefore, it should be applied into the soil by special machines. The problems encountered are similar to those with slurry application. Liquid fertilizers are very suitable for injection fertilization into deeper layers for trees by using special lances with fixed top and lateral nozzles.

The application of liquid fertilizers to soils has advantages and disadvantages:

➤ advantages:

- application of dissolved and, thus, immediately available nutrients,
- simple filling procedure of containers by pumps (labour-saving),
- very precise fertilizer distribution (superior to spreading of solids),
- large area can be fertilized in a short time (5–10 ha/hour),
- fertilization can be combined with compatible crop protection sprays;

➤ disadvantages:

- nutrients in soluble forms (liquids) are generally more expensive than those in solid forms,
- large amount of water must be transported,
- complete fertilization is rarely possible, hence, application of solids is also needed,
- transportation and storage requires expensive tanks and safety measures,
- nozzles must be corrosion-resistant,
- handling is generally more expensive than with solid fertilizers.

Application of gaseous fertilizers

In practice, fertilization with gases is restricted to anhydrous ammonia. It is a widespread practice in countries with large farms, a low ammonia price and high cost of solid N fertilizers (e.g. the United States of America). Anhydrous ammonia is applied from pressurized tanks. It leaves the distributing device as a gas after the pressure has been released and enters the soil as a gas. The problem with its application is in correctly dosing the liquefied gas at a pressure of about 1 000 kPa from the field tank with the aid of pumps and allowing for the speed of travel, temperature, etc. Pressurized ammonia is subject to special safety regulations concerning the strength of containers and pipelines, corrosion damage, possible injury to the operators, and toxicity of the gas.

Anhydrous ammonia is best applied into bare soil. It must be injected sufficiently deeply into the soil in order to avoid losses by evaporation. This is minimized by devices with special injection prongs that disturb the soil as little as possible, so that no opening at the surface is left. It can also be introduced into the soil by lances as in the case of liquid fertilizers. A precondition for this is to maintain the soil at medium soil moisture level, i.e. the soil must be neither too wet nor too dry.

Foliar fertilization

Leaves absorb nutrients as a natural process by which plants obtain additional nutrients from rainwater. This principle is utilized in agriculture by spraying the foliage with dilute solutions of the desired nutrients. Foliar fertilization is generally recommended for supplying additional N, Mg and micronutrients, but it can also be used to provide P, K and S.

Role of foliar fertilization

In practical farming, foliar fertilization is used as a quick remedy for unexpected deficiencies, for late supply of N during advanced growth stages, as a preventive measure against unsuspected (hidden) deficiencies, and to overcome fixation of nutrients in soils (e.g. Cu, Fe, Mn and Zn). The main advantage of foliar fertilization is the immediate uptake of the nutrients applied. Its shortcoming is the limited amounts that can be supplied. Nutrients present in inorganic salts or in chelated forms can be used for foliar application. The materials suitable for foliar fertilization have been described in Chapter 5.

For foliar application to be effective, a substantial amount of the deficient nutrient must be added, but it should not cause plant damage, leaf scorching, and negative osmotic effects. The solutions must be dilute (1–2 percent), especially if they contain nutrient salts. Foliar fertilization is at the best a supplement to soil application and not a substitute for it. Crops are less sensitive to organic compounds because they have only a slight osmotic action. Therefore, urea is better tolerated by leaves than is nitrate or ammonia and it enables the application of concentrations up to 15 percent with low-volume sprayers. Where urea is used

for foliar sprays, it should contain no more than 0.25 percent biuret. The same applies to micronutrient sprays through chelates vs inorganic salts.

With the exception of N, foliar application can supply only very limited amounts of the major nutrients such as P and K compared with their total requirements. The situation is a little better for Ca, Mg and S, but even these can be added only in limited amounts, which are often insufficient in a single application. The best results are obtained with micronutrients because a relatively large portion of the total requirement can be supplied in a single spraying. In cases of marked deficiencies or mobility problems within the leaf, repeated sprayings with micronutrients are essential, as in the case of Fe and Mn. Foliar fertilization can be combined with crop protection spraying, but the mixed components must be compatible.

Practical operation of foliar application

For foliar application, several types of sprayers are employed. A greater volume of solution is required per unit of area in the case of high-volume sprayers. The commonly employed procedures involve: (i) spraying about 400 litres/ha of a solution in fine 0.1–0.2-mm droplets; or (ii) high-pressure, low-volume spraying where the solution is blown at the leaves in very small droplets. Higher nutrient concentrations can be used with low-volume sprayers than with high-volume sprayers. In either case, there should be good adhesion of the solution to the leaves. This can be improved by adding special detergents and stickers.

Spraying is most effective, and the risk of scorch is minimized, where the spray droplets do not dry rapidly. This is best achieved by spraying on cloudy days or in the early morning or late afternoon. Application of N solutions should be avoided during the early growth stages. In the case of multiple deficiencies, combinations of nutrients are applied with special combined fertilizers, containing for example N, Mg and micronutrients. Per-hectare amounts up to 30 kg N, 1 kg Mg and 0.1–0.5 kg micronutrients can be applied in a single foliar spray.

During foliar fertilization, it is important to maintain the proper concentration suitable for the particular crop. This is usually stated on the bags containing special foliar fertilizers. Some general figures for concentrations are given below for foliar fertilization on certain crops at 400 litres/ha using solid fertilizers:

- urea (46 percent N):
 - solution of 8–15 percent = 14–28 kg N/ha for cereals, oilseed rape, etc.,
 - solution of 2.5–5 percent = 5–10 kg N/ha for beets and potatoes,
 - solution of 0.5–1 percent = 1–2 kg N/ha for fruit trees, vegetables;
- magnesium sulphate (10 percent Mg): solution of 2 percent = 0.8 kg Mg/ha for cereals and fruit trees;
- iron chelate (5 percent Fe): solution of 0.2 percent = 0.04 kg Fe/ha for fruit trees;
- manganese sulphate (24 percent Mn): solution of 1 percent = 1 kg Mn/ha for cereals;

- copper chelate (14 percent Cu): solution of 0.13 percent = 0.07 kg Cu/ha for cereals;
- Solubor, Octoborate (20 percent B): solution of 1.5 percent = 1.2 kg B/ha for beets and oilseed rape.

Fertilization through irrigation (fertigation)

In fertigation, fertilization is combined with irrigation, and the nutrients are supplied together with the water. In reality, it is a type of liquid fertilization. In the past, mainly N was added to water in furrows and through sprinkler irrigation. However, with the increasing use of microirrigation, fertigation on a precisely controlled small scale (microfertigation) has been developed. Beyond maximizing yields and quality of crops, the aim of fertigation is improved utilization of nutrients and lower water consumption, while minimizing pollution by surplus nutrients. The saving may be up to 30–50 percent of water and nutrients. Fertigation can improve crop yields in fields and greenhouses substantially. N utilization is higher and there are reduced losses through nitrate leaching. In addition, plants take up more phosphate compared with P placement, and the uptake of other nutrients is also enhanced.

The nutrient application process

Microirrigation distributes the nutrient solution to individual plants via drip or trickle irrigation operating at about 100 kPa pressure, or via minisprinklers operating at about 200 kPa pressure. The advantage is a constant supply of soluble (available) nutrients right into the rooting zone in order to meet the daily crop demand. The goal is to feed the plants in synchronization with their growing nutrient requirements. However, establishment and application costs are generally much higher than for broadcast fertilization combined with sprinkler irrigation.

Drip irrigation produces small zones of wet soil volumes with relatively uniform water content. The distance of nutrient movement from the input point differs from one nutrient to another. Nitrate and sulphate are transported farther than phosphate, which is more liable to immobilization near the site of deposit but less so than with broadcasting or adsorbed cations of K or Mg. As in the case of broadcasting, processes in the rhizosphere may affect nutrient uptake through fertigation as well. Fertigation of a partial soil volume with a confined root system allows a precise control of nutrient supply, thus, avoiding deficiencies or excess, as well as salinity hazards (except on poorly drained clay soils). The size of the root systems can be modified to some extent, but smaller volumes need better control of nutrient supply.

Suitable fertilizers for fertigation

Fertilizers for fertigation must be readily and fully water soluble, and the combined solution should be within the acidic pH range (about pH 5) in order to ensure nutrient mobility and availability. Nitrate and urea are better distributed in soils than is ammonium and, therefore, they are more suitable.

The main difficulties are with the common phosphates and even with polyphosphates because of their potential precipitation as Ca phosphates. Because of this, acidic P fertilizers such as phosphoric acid (e.g. 1 g/litre of pH 2.2), MAP, mono-potassium phosphate (MPP) and the more expensive urea phosphate or glycero-phosphate are often recommended. Of the K fertilizers, potassium nitrate and potassium sulphate are preferred to MOP because they contain no salinity-causing chloride. Recent research in Israel has shown that KCl can partly replace KNO_3 in fertigated tomatoes without adversely affecting growth and yield (Imas, 2004). The mixing of fertilizers must be undertaken carefully to avoid mistakes or compatibility problems. Moreover, an unwanted early precipitation of micronutrients in the soil can be avoided by using chelates such as EDTA, or more stable ones such as DTPA and EDDHA in soils of neutral reaction. Iron chelates are more effective than those of Mn or Zn.

Operational aspects

Fertigation requires corrosion-resistant mixing and pumping equipment and small lateral tubes for distribution of the nutrient solution through special nozzles. The lateral tubes can either be put on top of the soil or installed as subsurface fertigation. With the latter system, the nutrients are delivered into the centre of the root system, the root volume is increased and the rootless topsoil layer is kept dry. This has the advantage of reducing weed growth, but crop germination and establishment must be assured. Early plant growth is stimulated by pre-plant fertilization through broadcasting or placement, and this improves the efficiency of fertigation.

Fertigation requires special management skills as a breakdown in the system can have serious consequences. The composition of the nutrient solution and its uninterrupted flow must be controlled carefully. The nutrient composition is based on the daily consumption rate of the crops in the field. This can be obtained from guidelines for different crops. The crop growth is generally divided into ten segments in order to aid nutrient management. The required nutrient rates (expressed in kilograms per hectare per day) are in the range of 0.3–6 for N, 0.05–0.8 for P and 0.3–10 for K. The nutrient concentration must be high enough to produce high yields but must not cause salinity damage or related problems. A suitable concentration of the irrigation water is about 100 mg/litre (0.01 percent) of N and K.

A special problem with fertigation is clogging of the solution emitters. These can become blocked by precipitation of carbonates and/or phosphates, by suspended particles, by a biofilm of microflora or by fine roots. Special cleaning methods have been developed to prevent and remove the substances causing the blockages. Because of the complex application technology, fertigation is suitable only for advanced farmers and it requires considerable capital investment. Careful and frequent monitoring is required, preferably using simple field methods applicable to the farmer. A more detailed discussion of this topic can be found in Bar-Yosef (1999).

Hydroponics

Hydroponics is a system where the plant roots grow in a nutrient solution instead of the soil. Although soils are the “natural” growth substrate for plants, soil-less crop cultivation has been employed successfully. With intensive hydroponics, very high yields can be produced. However, it requires special equipment such as corrosion-resistant containers and pumps, devices for measuring out solutions of salts and acids, and suitable analytical instruments.

Ingredients required

The major ingredient is a suitable water supply, such as rainwater, which is low in mineral components. The fertilizers used must be water-soluble solids or liquids that can be mixed easily to prepare a concentrated stock solution. The required dilute nutrient solution is prepared from this stock solution by dosage pumps. A reliable monitoring system is essential for a well-functioning hydroponics system in order to maintain the correct composition of nutrients and to keep the salinity within a tolerable range. The solution has to be checked frequently by measuring its electrical conductivity.

Common fertilizers containing major nutrients for making the stock solutions are:

- salts: NH_4NO_3 , $\text{Mg}(\text{NO}_3)_2$, $\text{Ca}(\text{NO}_3)_2$, K_2SO_4 , KH_2PO_4 , and MgSO_4 ;
- acids and alkali: HNO_3 , H_3PO_4 , and H_2SO_4 ; KOH for pH adjustment.

Micronutrients are added as salts or chelates in the required low concentration.

The composition of the nutrient solution depends on crop requirement and growth stage. It generally has a total soluble-salt concentration of 0.2–0.7 mg/litre (1–2 mS electrical conductivity); N and K each at about 0.1–0.2 mg/litre, P about 0.01 mg/litre and a pH of 4–5.

Nutrient supply

The different techniques of nutrient supply are: (i) static solutions that are changed at certain intervals; (ii) flowing or cycling solution where the original concentration is maintained by dosing; and (iii) supply of solution over short intervals alternating with water. Compared with fertigation, the advantage of hydroponics is an even better control of optimal plant nutrition as there are no soil-related complications such as fixation of applied nutrients. On the other hand, the investments and the needs for control are higher. The advantages for plant nutrition via hydroponics are best utilized where other growth factors, such as temperature and CO_2 , are controlled. Because soils are not required, hydroponics can be used in locations with poor or no agricultural soil.

As with any production system, hydroponics has its advantages and disadvantages:

- advantages:

- nutrients are supplied in soluble forms and remain easily available,
- the nutrient solution contains the whole range of nutrients with optimal ratios,

- the solution can be adapted easily to changing plant requirements during growth,
- no toxic substances are present to disturb plant growth;

➤ disadvantages:

- there is no buffering capacity in the event of deficiency or excess, therefore, good control is required,
- the oxygen supply to the roots is less than in soils, thus, an external air supply is required,
- roots have no solid anchorage, thus, mechanical support or an inert porous material is needed.

Precision fertilization

Variability and uncertainty are dominant features of field crop production. There are differences between nutrients in the type of variation encountered in field situations. For P and K, the variation is mainly spatial and location-related, but for N there is an additional large temporal (time-related) variation. These are difficult to account for with traditional fertilizer application methods. The common fertilizer application method is based on the reasonable assumption that, from a practical point of view, the soil nutrient supply to small fields of up to about 1 ha is more or less homogenous. Where on larger fields there are nutrient-related soil differences, the area can be divided into homogenous subunits of any suitable size and treated individually. With this modification, the common method of fertilizer distribution has been and still is successfully used in many parts of the world.

Much of the intrafield variability can be overcome by precision farming. This approach applies modern technologies to manage variability in space and time in order to improve crop performance and decrease nutrient losses. Precision farming is applicable to many aspects of crop production, such as soil fertility and plant protection management. The main objective is to produce uniform high yields over the whole field, economize on fertilizer and pesticide inputs, and create minimal undesirable effects on the environment. In order to be adopted widely, it needs to be efficient and profitable.

Precision fertilization presents a special method for distributing fertilizers according to the different needs of small plant populations caused by soil variability within a field. Such a concept is very promising for areas where fertilization practices have advanced over the years. It is based on:

- precise location control for both diagnosis and input application using systems such as the Global Positioning System (GPS);
- detailed assessment of soil fertility either by analysing distinct samples or recorded continuously by sensors of microllevel nutrient status and its variation in the field;
- comprehensive and rapid data processing;
- site-specific application of fertilizers to the small basic soil areas within the field.

The expected advantages of precision fertilization for the farmer are: (i) uniform nutrient supply to all parts of the field, which enables higher yields and product quality; (ii) savings in fertilizer rates; and (iii) lower nutrients losses. Although costly, modern precision fertilization is often profitable in commercial farming on a medium to large scale.

Prerequisites for precision fertilization

In order to practice precision fertilization, the technologies required are: a precise location control, a reliable assessment of microlevel variation, and equipment for site-specific applications, all coordinated by efficient computers using suitable software. For location control (knowing the exact position in the field), previous outmoded methods used for land survey have been replaced by the GPS, which permits the monitoring of even very small areas (100 m^2), which are called pedocells.

Assessment of the nutrient status of each pedocell is the backbone of precision fertilization. Without it, there can be no precise fertilizer application. Most weaknesses in the system are related to this central problem. Compared with cumbersome chemical soil testing, special sensors reacting to different light effects are much more efficient. However, sensoring of soil fertility aspects such as available nutrients is not yet possible. The equipment for precision nutrient application requires highly developed steering devices and devices for changing application rates quickly and distributing them accurately. For example, suitable centrifugal fertilizer distributors for quick changes in precise dosages are now available but they are expensive.

The absence of sensors for the actual diagnosis of soil nutrient status and the lack of inexpensive production of detailed nutrient maps will remain as obstacles in the adoption of precision fertilization. The preconditions for an efficient and cost-effective precision fertilization are: its capability to take into account large spatial differences in relatively small areas; simple provision of cheap diagnostic methods – preferably with sensors; and production of reliable soil fertility maps.

Precision soil fertility management

There are many possibilities and problems concerning the “precise distribution” of major nutrients. Precision farming offers great possibilities for improved nutrient supply to most plants by overcoming yield-limiting or fertilizer-wasting effects associated with natural or human-made variations within a field. Many aspects of precision fertilization have been discussed by Pierce and Nowak (1999).

The advantages of precision fertilization appear obvious and raise high expectations. However, the sceptical farmer who is advised to invest in modern precision technology would like to examine the system critically before adopting it, particularly the following aspects.

The relevant comparison of common fertilizer distribution with precision fertilization should not refer to uniform distribution of fertilizers on the whole field but to the customary method of differential fertilizer application. Where

fertilization is based on soil testing, the principle of uniform fertilization applies only to uniform parts of a field from which separate test sample have been taken. This method takes into account the differences that are noticeable in the field, while ignoring small differences. Although this appears to be a rather crude method in comparison with precision fertilization, it is relatively effective.

Considering the inherent inaccuracies in soil sampling and soil testing, a detailed map would require an enormous number of samples. Where extrapolation procedures are based only on a few samples, this requires a sophisticated interpretation method. Although scientifically sound, both procedures have practical problems. For medium to high yields, a small surplus P and K application can be advantageous for adequate nutrient supply during nutritional stress. Because the available phosphate concentration is low and variable in time, there are no P-surplus problems for crops, and as there is hardly any leaching of phosphate, overfertilization of parts of the field is tolerable although not ideal or cost-effective.

Precision fertilization can be efficient and profitable where intrafield variability can be assessed reliably and economically. It will not be profitable where the diagnostic assessment remains expensive and unreliable and also where high level uniformity is neither required nor brings about significant yield increases. In most cases, it is not of much interest to smallholders with severe financial constraints in many developing countries. However, it is a valuable tool for large farms, organized plantations and for the large-scale production of high-value crops.

For an average farmer in many countries, the main question is not whether precision fertilization is useful or not but whether it is worthwhile. Many such farmers are in the very early stages of development in terms of scientific farming and optimizing plant nutrition. They are still some way away even from adopting blanket fertilizer recommendations made for their region or conventional soil-test-based fertilizer rates. It is for this reason that this guidebook does not include the nutrient details of precision fertilization. This in no way undermines the usefulness of precision farming.

GUIDELINES FOR THE APPLICATION OF ORGANIC MANURES

Application of solid manures

Bulky organic manures such as composts and FYM can be applied to all soils and almost all crops, as can oilcakes, recycled wastes and animal meals. In order to make best use of the slowly acting N, these should be applied a few weeks before sowing, spread uniformly over the field and immediately ploughed into the soil in order to avoid ammonia losses. Common application rates are about 20 tonnes/ha but range from 10 to 40 tonnes/ha. While large amounts are spread over the whole area, smaller amounts are preferably concentrated in plant rows or applied around the base of individual trees or bushes. Vermicompost is normally applied to the soil in the same manner as bulky organic manures. The commonly recommended rate for mature vermicompost is 5 tonnes/ha.

Many farmers use whatever quantities are available on the farm or in nearby areas. With 20 tonnes/ha of FYM, about 100 kg N/ha is added. In the first year,

20–30 percent of this N is utilized, but up to 40–50 percent can be utilized by the second year, including the residual effect.

Application of slurries

Slurry can be obtained from farm animals raised in organized dairy farms. Animal slurry is the major manure in many developed countries where cattle are raised on a large scale. Other forms of slurries are obtained from the treatment of sewage and from biogas plants.

Application of animal slurry

The common practice of spreading animal slurry on the soil surface results in substantial losses of ammonia where the slurry is not mixed immediately into the soil. N losses are reduced by modern drilling machines that place slurry a few centimetres into the, preferably, moist soil. In this respect, it is similar to suspension fertilizers.

The recommended application rates of animal slurry are related to the crops, e.g. 30–40 m³/ha (75–200 kg/ha N) for winter cereals, applied partly in autumn and partly in spring; and 40 m³/ha for silage maize in spring and the same on grassland for hay production. For accurate N application, the exact N concentration of the slurry should be known and special precautions must be observed where it is applied on growing plants both in order not to damage the plants and for health reasons. No slurry should be applied on vegetables intended for fresh consumption or on meadows at least one month before grazing starts. After that, it can be applied only if it is well fermented.

In some countries, legislation regulates the maximum rate of slurry application in order to prevent environmental damage caused by ammonia losses and the leaching of nitrate. It would be advantageous if slurry could be transformed into a solid product such as compost with more suitable application properties, but so far this has not been economically feasible.

Slurry obtained from biogas plants is also a kind of animal slurry as cattle dung is the most common feedstock used in biogas plants. It is a semi-solid product and is better than FYM as a manure because it is well digested and has a higher nutrient content. However, it is difficult to transport. In the case of small biogas plants (based typically on the dung of five head of cattle), the slurry is usually spread on the farmland near the biogas plant. An alternative method for using biogas plant slurry is to convert it into a compost. The use of biogas slurry in proper combination with mineral fertilizers is one of the major possibilities for INM.

Application of sewage (wastewater) and sewage sludge

In many countries, sewage sludge is rarely used directly as a nutrient source by applying it on bare soil. Because this procedure has health risks, wet sewage sludge is converted into a moist or dry solid product and possibly processed into sludge compost. Application rates of 2–3 tonnes/ha on a dry-matter basis are advisable, but they should not exceed 5 tonnes/ha within 3 years. As with any nutrient

source, sewage sludge should not contain more than the critical concentrations of toxic elements and should only be applied to soils that contain such elements well below the critical toxic levels. This will prevent damage to soil health, crops, food quality and feed value. Farmers in developed countries have become less enthusiastic about using cheap city wastes as a nutrient source because of the ever-increasing regulations involved and the uncertainties about future regulatory aspects.

Wastewater reuse for crop irrigation and nutrient supply becomes particularly attractive where it is planned in conjunction with environmental safeguards. The wastewater must be treated and used in such a way that its content will not be hazardous to human beings or the environment. In order to protect public health, the effluent should either be treated properly before irrigation application, or its use should normally be restricted only to certain crops so that improperly treated wastewater does not come into contact with plants used for direct consumption as human food or animal feed. A suggested cropping list for irrigation with differentially treated wastewater for semi-arid tropical conditions in developing countries is as follows (Juwarkar *et al.*, 1992):

- primary treated:
 - cash crops: cotton, jute, sugar cane, tobacco,
 - essential oil crop: citronella, mentha, lemon grass,
 - cereals and pulses: wheat, rice, sorghum, pearl millet, green gram, black gram,
 - oilseeds: linseed, sesamum, castor, sunflower, soybean, groundnut,
 - vegetables: brinjals, beans, okra, etc. These should be cooked before eating;
- secondary treated:
 - all crops listed above,
 - all crops including vegetables that develop near or below the soil surface but are only to be consumed after cooking;
- secondary treated and disinfected:
 - all crops without restriction.

Optimal rates and intervals of wastewater application to agricultural soils should be determined primarily by crop needs and soil health considerations and not merely as an outlet for waste disposal. As with any other farm input, there is an optimal level that needs to be borne in mind for different soils and crops. Excessive loading with wastewater may lead to soil sickness, which can be corrected through adequate resting of the soil from crop production and use of soil amendments.

Application of green manure

Green manure can be either grown *in situ* and incorporated in the main field or grown elsewhere and brought in for incorporation in the field to be manured. Not all plants can be used as a green manure in practical farming. Some plants suitable for green manuring have been described in Chapter 5. Most plants used as green

manures are legumes. As green manures add whatever they have absorbed from the soil, they also promote the recycling of soil nutrients from lower depths to the topsoil. The net gain is only in the case of biologically fixed N.

Green leaf manure consists of fresh green leaves of suitable plants grown on the bunds of the main field or elsewhere and brought in for incorporation in the soil. Green leaves of these plants are incorporated in the soil at or before planting the main crop.

In selecting a green manure crop, the most desirable characteristics are: (i) local adaptability of the plant; (ii) fast growth and production of a large amount of green matter (biomass)/unit area/unit time; (iii) tolerance to soil and environmental stresses, such as acidity, alkalinity, and drought; (iv) resistance to pests; and (v) easy decomposability – requiring least time between the incorporation and planting of the main crop. Where a green manure crop is raised before taking a wetland rice crop, it can be ploughed in even a few days before planting rice. Where the green manure is raised before maize, potato or sugar cane, it should be buried and incorporated in the soil 2–3 weeks before planting the main crop.

GUIDELINES FOR THE APPLICATION OF BIOFERTILIZERS

Biofertilizers can be applied to the seed, to the soil or to the roots of seedlings before these are transplanted in the main field. It is most important to know that not all biofertilizers are suitable for all soils and crops. Various biofertilizers have been described in Chapter 5. In general terms, the applicability and usefulness of biofertilizers for different crops can be stated as follows:

- cereals:
 - rice (wetland): BGA, *Azolla*,
 - others: *Azotobacter*, *Azospirillum*, PSB;
- pulses: *Rhizobium*, PSB;
- oilseeds:
 - legumes: *Rhizobium*, PSB,
 - non-legumes: *Azotobacter*, PSB;
- pastures, forages and fodders:
 - legumes: *Rhizobium*, PSB,
 - non-legumes: *Azospirillum*, PSB;
- forest trees:
 - legumes: *Rhizobium*,
 - casuarina: Frankia, PSB, mycorrhizae,
 - others: *Azotobacter*, mycorrhizae;
- others:
 - potato, cotton: *Azotobacter*, *Azospirillum*, PSB,
 - sugar cane: *Azotobacter*, *Azospirillum*, *Acetobacter*, PSB,
 - citrus: mycorrhizae, *Azotobacter*, PSM,
 - tobacco: *Azotobacter*,
 - plantation crops: *Azotobacter*, mycorrhizae,
 - vegetable crops, flowers/ornamental plants, spices: *Azotobacter*, PSB.

The most common method for the application of bacterial inoculants is by coating them on the seeds before sowing. Other methods include soil application by mixing the inoculum with organic manure and spreading the mixture on the nursery area, main field or in the furrows. Setts of sugar cane, cut tubers of seed potato and roots of seedlings can also be dipped in the biofertilizer slurry before planting in the main field. For example, cut tubers of seed potato can be soaked for 20–30 minutes in 50–60 litres of suspension containing 1 kg of biofertilizer.

Application of *Rhizobium* inoculant

Rhizobium inoculant is the most commonly used biofertilizer. It is specifically intended for application to legumes. It is very important to select the correct *Rhizobium* inoculant (Chapter 5). Generally, a significant beneficial effect from using *Rhizobium* biofertilizer can be expected where the native *Rhizobium* population is less than 100 cells/g of soil. It is important to check that the correct species of *Rhizobium* is being used for the crop to be treated and that the commercial inoculant is of acceptable quality and well within the stated date of expiry. The following biofertilizer application techniques have been adapted from Motsara, Bhattacharayya and Srivastava (1995). The procedure for inoculating the seeds of legumes consists of the following steps:

- First, a slurry of the biofertilizer is to be prepared. This can be done by adding 125 g of country sugar (unrefined cane sugar) to 1.25 litres of water and heating for 15 minutes. Where gum acacia has been added to the product as adhesive, farmers are advised to follow the instructions on the packet. As an alternative to country sugar, 500 g of gum arabic can be added, and the solution is cooled to room temperature.
- The inoculant (400–500 g) is mixed into the above sugar or gum-acacia suspension to form a slurry. To this, the seeds required to plant 1 ha are added and mixed thoroughly by hand. Finally, the seeds are dried in shade on a plastic sheet/paper and sown without delay.

Rhizobium bacteria are sensitive to low pH. Their tolerance to pH varies with species in the order: *B. japonicum* > *B. lupini* > *R. leguminosarum* > *R. trifolii* > *R. phaseoli* > *R. meliloti*. In acid soils, lime may have to be applied in order to create favourable conditions for their survival. Mo availability is also low in acid soils. As Mo is required for BNF, Mo sometimes has to be supplied as an external input. It can be added with the inoculum onto the seed. In areas where such cultures are not available, soil collected from another field under the same crop can be used.

The efficiency of BNF also depends on the adequate availability of nutrients that are required by the legume and the N-fixation system. Several plant nutrients in the soil can affect nodulation and N fixation:

- Ca and B have been shown to be involved in infection and nodule development.
- In moderately acid soils, the Ca requirement for nodule infection is higher than that of the host plant.
- B deficiency inhibits the formation of vascular strands from roots to nodules.

TABLE 37
Suitable quantities of *Rhizobium* inoculant and sticker for inoculating legume seeds

Legume	Seed weight	Inoculant	Gum arabic solution
	(g)		(ml)
Groundnut	100	10	4.0
Chickpea	100	7	3.5
Pigeon pea	100	8	3.5
Soybean	100	10	3.0
Lentil	50	5	2.0
<i>Leucaena leucocephala</i>	50	10	3.0
Green gram	100	9	3.5
Cowpea	100	8	3.5

Source: Motsara, Bhattacharayya and Srivastava (1995).

of the day should be avoided. The amounts of culture, water and sticker needed per hectare depend on the seed size and seed rate because the objective is to coat/cover all the seed with the biofertilizer slurry. There should be a minimum gap of 24 hours between seed treatment with a fungicide and biofertilizer in order to avoid any harmful effect of the agrochemical on the micro-organisms in the biofertilizer.

Table 37 provides a general idea of the suitable quantities of inoculant (biofertilizer) and sticker required for various legumes.

Preparation of methyl-cellulose solution for seed-coating

Seeds can also be coated with biofertilizer by using a 1-percent methyl cellulose solution for coating. To prepare the solution, methyl cellulose is weighed at the rate of 1 g/100 ml and sprinkled into about 50 ml of hot water (about 80 °C). This is stirred well and any lumps formed are broken. After it has dissolved, the remaining cold water (50 ml) is added while stirring to obtain the required volume. A fine gel is formed that can be coated on the seeds. First, a slurry is prepared by mixing and stirring the inoculant at the rate of 70 g in 300 ml of 1-percent methyl-cellulose solution. The thoroughly dispersed slurry is then poured over the correct weight of seeds (e.g. 300 ml/20 kg chickpea seeds) and mixed until all the seeds are coated. Mixing can be done in a vessel or on a plastic sheet. Any vessel contaminated with toxic materials or dust should not be used for mixing. The seeds are dried in shade, kept away from direct sunlight, and sown as soon as possible.

Tree/legume seedlings can be readily inoculated in the nursery. A 50-g bag of inoculant is sufficient to inoculate 10 000 seedlings (regardless of species). This can be done by mixing the culture in cool water and using the suspension to irrigate the rooting medium of the seedlings.

Application through pelleted biofertilizer

Many bacteria are sensitive to acidic conditions and also to hot and dry weather. They can be protected from these adverse factors by application in pelleted

➤ The effect of P on N fixation is through its effect on overall plant growth.

➤ Mo, Fe and S are components of the nitrogenase enzyme, which is involved in the N-fixation process.

➤ Co is part of the cobamide coenzyme.

➤ Fe is a component of leghaemoglobin, which carries oxygen to the bacteria inside the cell.

Sowing during the hot period

form. If the inoculated seed is coated with powder lime, it gives good protection, especially where the soils are very acid, hot and dry. Pelleting can also help to protect the seeds from insects, especially seed-gathering ants. Calcium carbonate is the most common and beneficial of the many materials tested. Quicklime should not be used as it is highly toxic.

Seed pelleting with biofertilizer can be done as follows:

- The appropriate quantities of gum arabic and water to be used with the desired quantity of the particular seed to be pelleted are calculated. Gum arabic dissolves in cold water if left overnight and in hot water in about 30 minutes. The solution should not be boiled. The gum-arabic solution is cooled. The appropriate amount of inoculant is added to the solution and stirred to form a smooth slurry. This mixture must not stand for more than 30 minutes. Some gum arabic is acidic and will harm the bacteria unless the acid is neutralized by calcium carbonate as soon as possible.
- Small lots of seeds may be pelleted by hand, in a tub, bucket or on a smooth floor. For pelleting large quantities of seeds, a mechanical mixer can be used (seed drum, cement mixer, etc.). Vigorous agitators from the mixing equipment should be removed in order to prevent damage to the pellet coating.
- The seeds are poured into the mixer and then the gum inoculant slurry is added. The mixer is then rotated at high speed until all the seeds are coated. Without stopping the mixer, calcium carbonate is added all at once, and the mixer allowed to run until all the seeds have been pelleted.
- The mixer should not be cleaned between loads. After the whole job is done, the mixer is cleaned by running a load of water and gravel through it. Pellets are firmer if they are allowed to stand for 24 hours and these work better in a seed drill.
- The pelleted seeds are screened to remove any lumps in order to avoid clogging the seeding equipment. Where there is an excess of calcium carbonate powder, it is screened to prevent clogging of the seeding equipment.

Precautions

Rhizobium inoculation sometimes fails to give the expected results. This can be because of the following reasons:

- the soil already contains a sufficient population of effective and required strains of *Rhizobium*;
- poor quality of inoculum, which is unable to compete with the native bacteria;
- suboptimal (low dose) level of inoculum used;
- presence of toxic substances associated with seed-coat (e.g. phenolic compounds and condensed tannins);
- existence of biological antagonists, e.g. rhizophage, nematodes;
- inoculation applied with agrochemicals that are toxic to micro-organisms (e.g. thiram, bavistin and chlorpyrifos);

- poor soil conditions viz. acid soils (low pH), waterlogging, high soil temperature, etc.;
- low or excess soil moisture restricting the movement and proliferation of *Rhizobia*;
- nutritional stresses, e.g. deficiency of P, B and Mo.

Azotobacter

The application of *Azotobacter* inoculant involves making a slurry of the carrier-based biofertilizer using a minimum amount of water. The seeds are mixed with the slurry as in the case of *Rhizobium*, dried in shade and sown as soon as possible. For transplanted crops, the roots of seedlings can be dipped in the slurry for 20–30 minutes and then transplanted. In the case of sugar cane, *Azotobacter* application may be needed more than once during early growth. In this case, second and further treatments can be given by pouring the slurry near the rootzone. The slurry can also be mixed with FYM and applied near the rootzone.

Blue green algae (BGA)

BGA are a biofertilizer specific to wet paddy fields. The BGA can be inoculated in fresh form, dry form or as soil-based inoculum. Inoculation of fresh BGA is better than dry BGA or soil-based inoculum. This is because fresh BGA establish early in paddy fields and grow faster. Fresh BGA at the rate of 30–60 kg/ha and dry BGA or soil-based inoculum at 5–10 kg/ha is recommended for multiplication plots and transplanted paddy fields. Application of dried BGA flakes at the rate of 10 kg/ha is recommended for the main rice field. The flakes are to be applied ten days after transplanting rice. For best performance of BGA, the field should have an adequate level of available P. A thin film of water is maintained over the field. BGA multiply well in warm weather.

Azolla

As in case of BGA, *Azolla* is also used as a biofertilizer, primarily in wetland rice culture. It is in fact different from most other biofertilizers in that its biomass is incorporated in the soil just as in the case of a green manure. It can be used either as a conventional green manure before planting rice or grown as a dual crop along with rice and then incorporated in the soil while the rice is still growing.

Azolla as a green manure

The field is ploughed and levelled about 15 days before transplanting rice. It is subdivided into plots of 300–400 m² each. The subplots are flooded and puddled properly, after which 5–10 cm standing water is maintained. Fresh *Azolla* can be inoculated at the rate of 3–4 tonnes/ha (3–4 kg/10 m²). After 2–3 weeks, the water is drained from the field and the green *Azolla* biomass is incorporated into the soil. Rice is transplanted within a week. For satisfactory N fixation, the soil should not suffer from nutrient deficiencies, particularly those of P, and the temperature as well as moisture should be optimal (Chapter 5).

Azolla as a dual crop

In this case, *Azolla* is inoculated in standing water at the rate of 3–4 tonnes/ha 1–2 weeks after transplanting rice. It grows fast, multiplies and fixes N while the rice crop is growing. Dry *Azolla* spores can be used as an inoculum at the rate of 5 kg/ha in transplanted rice fields. These are pre-soaked in water for 12 hours and inoculated in the rice field seven days after transplanting rice. After 3–4 weeks, the water is drained and the *Azolla* is buried in the soil where it is growing and incorporated with a weeder or other suitable implement. Repeated incorporation of *Azolla* is needed. As a dual crop, *Azolla* can be grown more than once for the same rice crop in order to obtain additional benefit. On decomposition, it releases the fixed N and other nutrients in its biomass for use of the rice crop.

Azolla can be grown as a dual crop even after it has been incorporated as a green manure before planting rice. Usually, the amount of inoculum recommended is 0.1–0.3 kg/m² (1–3 tonnes/ha) for multiplication plots and 0.5–1.0 kg/m² (5–10 tonnes/ha) for dual cropping.

Phosphate-solubilizing biofertilizers

For the application of phosphate solubilizers, the best method is seed treatment. Other methods such as seedlings and soil can also be used. For seed treatment, a slurry is prepared using 200 g of biofertilizer in 200–500 ml. of water. This is then poured slowly over 10–25 kg seeds. The seeds are mixed evenly to obtain a uniform coating of the seeds. The treated seeds are dried and sown immediately, as in case of N-fixing bacterial inoculants. For soil treatment, a mixture of 5–8 kg of biofertilizer with 100–150 kg soil or compost is prepared and applied by surface broadcast over 1 ha either at sowing or 24 hours earlier. For the treatment of seedlings, a suspension of 1–2 kg biofertilizer is prepared in 10–15 litres of water. The roots of seedlings from 10–15 kg of seed are then dipped into this suspension for 20–30 minutes and transplanted soon after.

Mycorrhiza

Mycorrhiza (VAM) is a mobilizer of soil nutrients and an enhancer of root reach for plant nutrients. Mycorrhizal fungal spores are used to produce the inoculum.

The inoculation of mycorrhiza for nursery plants involves sowing the seeds and raising seedlings or bare root cutting in plastic bags or pots. In all these methods, 4–5 g of appropriate VAM inoculum is placed 3–5 cm below the seed or the lower portion of bare root cuttings, followed by normal plant cultivation practices. In the case of application to seedlings grown on raised seed beds, the appropriate inoculum is applied by soil incorporation. About 6 kg of inoculum is mixed with soil sufficient for 25 m² and covered with a thin layer of soil. In most cases, the population of seedlings is sufficient for transplanting 1 ha. It is necessary to remove the inoculated seedlings from the raised seed beds carefully so that the mycorrhizae associated with roots are not affected and are transferred effectively along with the seedling to be transplanted. For optimal benefits, root treatment

with a slurry of 250 g inocula in 1 litre of cow dung slurry can be given at the time of transplanting.

APPLICATION OF SOIL AMENDMENTS

Problem soils often require amendment before they can be cropped successfully and optimal use made of the plant nutrients applied. Liming of acid soils and reclamation of alkali soils are given here as examples.

Amendments for acid soils

Several liming materials have been described in Chapter 5. Generally, calcium carbonate is selected where it is readily available at reasonable cost. Where the soils also need Mg application, dolomite limestone is preferred. Basic slag and sugar-factory press mud from the carbonation plants also have a liming effect.

For some crops such as potatoes, liming ahead of planting is preferable because of their sensitivity to high soil pH after recent liming, which may cause scab owing to Mn deficiency. For “top-liming” of growing plants, only carbonate lime should be used in order to avoid leaf scorch. For grassland, lime is spread on top of short grass in spring, left to dissolve and allowed to be washed into the topsoil.

The liming material should be distributed evenly on the bare soil and then mixed well into the topsoil layer in order to achieve a uniform increase in soil reaction. Application after harvest but before tillage and sowing (sometimes termed “stubble liming”) is the best procedure. Following this practice, the soil layer below the topsoil can also be ameliorated to a certain extent.

Liming of fields is generally required every 3–5 years or once in a crop rotation. It should be done on priority for crops such as sugar beet and oilseed rape, which do not grow well under acidic conditions and prefer higher soil pH. In general, except for crops such as tea, which must have an acidic environment, liming is recommended for bringing the pH towards neutrality and, in the process, improving the availability of several nutrients.

Amounts of lime required

The lime requirement cannot be calculated directly from the pH value because of the need to also neutralize reserve acidity, which is not reflected in the pH value. However, a knowledge of pH and soil texture can be used to approximate the amount of limestone needed. Generally, the target is to lime an acid soil to reach a pH of 6.5. Most soil-testing laboratories are able to provide information on soil reaction and soil texture. One method for determining the lime requirement is:

- Step 1: determination of H value from the pH measured in Ca acetate:
 - acetate pH of 6.5 corresponds to an H value of 3.5 meq/100 g;
 - acetate pH of 6.0 corresponds to an H value of 11 meq/100 g.
- Step 2: From the H value, the lime requirement to reach pH 7 (neutral) can be calculated:
 - 1 meq H/100 g = 0.84 tonnes/ha CaO for top 20 cm of soil weighing 3 000 tonnes/ha.

Table 38 provides a simple reference list for calculating the amount of lime required to treat acid soils of different textures. This amount is usually for treating the top 15 cm of soil. The amount of lime required will change proportionately as the depth of treatment changes.

Maximum amounts of lime

In Europe, the general advice is that the amounts of lime applied at one time must not exceed 2 tonnes/ha of carbonate lime on light soils and 3–5 tonnes/ha on medium and heavy-textured soils in order to ensure good mixing with the soil. Where a sufficient amount of limestone cannot be used, as in the case of wide-row crops, the furrows to be planted can be limed instead of spreading it on the entire field. This will economize on the lime required and still improve the pH in the rootzone.

Amendment of alkali (sodic) soils

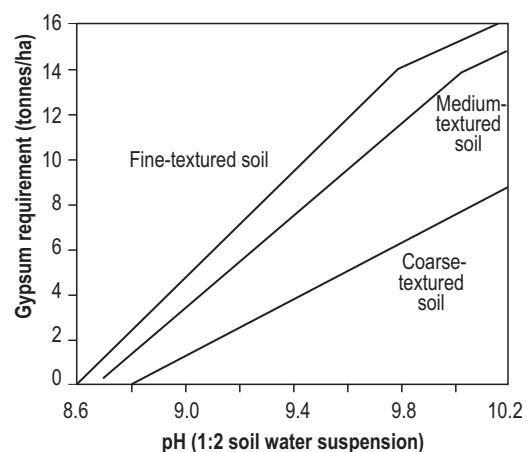
At the global level, about 434 million ha of soils are affected by alkalinity. Such soils have a very large percentage of their cation exchange site occupied by the undesirable sodium ions (Na^+). In highly sodic soils, 70–80 percent of the exchange positions are occupied by Na^+ leaving few places for useful nutrient cations. Amendment of such soils is a prerequisite for efficient nutrient management and obtaining high yields. As an amendment process, steps are needed to remove excess Na^+ from the exchange complex and replace it with Ca^{2+} and make the soil normal. As the ESP increases, so does the pH. Therefore, soil pH is also used as an indicator to decide the quantity of amendment required.

Based on soil pH and texture, the amount of gypsum, a common amendment, is recommended (Figure 41). It is generally sufficient to incorporate gypsum in the top 10–15 cm of soil. Gypsum required to replace all the Na^+ ions is referred to as 100-percent gypsum requirement. The amounts

TABLE 38
An example of the relation of soil pH and texture with lime requirement

Soil pH	Lime needed in soils of different texture		
	Sandy loam (kg/ha)	Loam (kg/ha)	Clay loam (kg/ha)
5.0	5 550	6 000	6 450
5.2	4 650	5 100	5 500
5.4	3 750	4 200	4 650
5.6	2 850	3 300	3 750
5.8	1 950	2 400	2 850
6.0	1 050	1 500	1 950
6.2	650	850	1 050

FIGURE 41
Relationship between pH and gypsum requirement in soils of different texture



Source: Bhumbra, 1974.

required increase where soils are to be treated up to a greater depth (which is often unnecessary). Mineral gypsum ground to pass through a 2-mm sieve is efficient and cost-effective. Adequate availability of good-quality water is required for leaching during the reclamation process. Crops raised on amended soils benefit from green manuring, which is an important part of INM.

Iron pyrites and elemental S-containing compounds have also been used to amend alkali soils. The availability, efficacy and cost-effectiveness of the material (as also ease of application) determine the final choice of the material to be used. The reclamation and management of salt-affected soils has been discussed in detail by Gupta and Abrol (1990).