Bio Factsheet

Number 87

The Biology of Fertilizers

This Factsheet covers the following areas of A-level syllabuses and specifications:
- **the need for fertilizers.**
- **types of fertilizers and their use.**
- **the ecological implications of the misuse of fertilizers.**
- **medical implications of the overuse of fertilizers.**
- **how problems caused by fertilizers can be avoided or overcome.**

Soil fertility and the need for fertilizers

Green plants are autotrophic in that they manufacture the carbohydrates, proteins, lipids and other organic compounds they require by photosynthesis. Some plant substances require inorganic elements and compounds for their manufacture (Table 1).

The metallic and non-metallic elements required by plants are obtained by absorption from the soil solution by root hairs. Nitrogen occurs as nitrate ions (NO_3^-), sulphur as sulphate ions (SO_4^{2-}) and phosphorus as phosphate ions (PO_4^{3-}).

The inorganic ions in the soil originally came from the rocks which gave rise to the soil. As plants use them up, or as they are washed out of the soil by rain (leached), they are replaced by the normal decay processes of animal and plant remains.

Within a stable natural ecosystem, over a period of time, the rate of uptake of inorganic nutrients from the soil would be balanced by the rate of return of inorganic nutrients to the soil. For instance, in a northern deciduous forest, as trees form leaves in the Spring and Summer herbaceous flowers grow and reproduce, there is a huge uptake of nutrients from the forest soil. In Autumn the leaves fall from deciduous trees and herbaceous plants die back, adding organic material to the soil, which can undergo decay, forming humus, which replenishes the soil nutrients. The decay processes are aerobic and rely on the soil being well drained, well aerated and with a good texture or crumb structure. Earthworms, when burrowing, tend to improve the aeration and drainage of soil, but also they secrete calcium ions which flocculate the soil particles forming crumbs.

In agriculture, when farmers grow and harvest crops year after year the system may become unbalanced since more nutrients are taken out of the soil than are replaced by normal decay. Thus the soil may become ‘exhausted’ and infertile. The problem may be alleviated by ploughing in plant remains such as corn crop stubble, by adding fertilizers and by practising crop rotation. Ploughing improves the drainage, aeration and texture of soil.

Table 1. Roles of minerals in plants

Mineral	Roles
Nitrate*	Reduced to nitrite by **nitrate reductase** during **amino acid synthesis**. Used in the synthesis of proteins, nucleic acids, chlorophyll and many coenzymes.
Phosphate*	Component of DNA and RNA and of energy carrying coenzymes, such as ATP. Component of phospholipids found in cell membranes.
Sulphate	Component of sulphur-containing amino acids (e.g.. cysteine) and some proteins. Component of coenzyme A. Deficiency causes ‘**chlorosis**’ (yellowing of leaves due to a failure in chlorophyll synthesis).
Magnesium*	Component of chlorophyll molecules. Deficiency causes ‘**chlorosis**’ due to a failure to synthesise chlorophylls. Magnesium pectate is a component of the middle lamella of cell walls.
Calcium*	Calcium pectate is the main component of the middle lamella of cell walls. Deficiency results in stunted growth due to poor cell wall development.
Iron	Needed as a cofactor in chlorophyll synthesis. It is a cofactor for peroxidase enzymes, such as catalase. Deficiency results in ‘**chlorosis**’ due to poor chlorophyll synthesis.
Zinc	Needed as a cofactor for alcohol dehydrogenase required for anaerobic respiration. Deficiency causes leaf malformations in some plants.
Potassium	Required as a cofactor for some photosynthetic enzymes. Deficiency causes yellow and brown leaf margins and premature leaf death.
Molybdenum	Needed as a cofactor for the enzyme **nitrate reductase** which catalyses the reduction of nitrate to nitrite during amino acid synthesis. Deficiency causes a reduction in growth rate.
Boron	Needed as a cofactor during mitosis in meristems. Deficiency results in abnormal growth and death of shoot tips, ‘stem-crack’ in celery and ‘heart-rot’ of beet.

* specifically named on most syllabuses/specifications.

In crop rotation, different crops are planted in successive years and these take different nutrients or different quantities of nutrients out of the soil. Thus the soil is not denuded of one particular group of minerals. In some years clover or other **Papillionaceous** plants, such as beans, are planted since these carry out nitrogen fixation (using symbiotic Rhizobium bacteria in their root nodules) and this adds nitrogen compounds to the soil. In some years the fields are allowed to lie fallow (no crops grown) which helps the soil to recover but is non-productive for the farmer. A year or two of grass, which can be grazed by cattle and sheep, improves the soil texture and the dung from the animals returns nutrients to the soil.

The trend in arable farming in recent years has been away from practising crop rotation and towards greater use of monoculture. In monoculture, the farmer grows large quantities of the same plant species year after year. What crops are grown is dependent on current market forces and often on economic subsidies which are paid for growing certain crops.

However, monoculture has two great disadvantages:

- it denudes the soil of the same nutrients, leading to soil exhaustion. This has to be remedied by continual use of fertilizers which, though restoring soil fertility, may cause pollution and health problems.

- it may cause a build up of parasites specific to the monoculture crop. These parasites may be fungal, insect or nematode worms and will require pesticides to be used to control them. In crop rotation the specific parasites only had one growing season to become established and multiply before other crops were planted which could not support them.

To help to meet the world's food needs, soils must be made to yield the greatest quantities of food possible but at the same time the productive capacity of the soil must be maintained or improved.

Types of fertiliser

There are two classes of fertilizer:

- **natural organic fertilizers** – examples are farmyard manure, animal dung from grazing farm animals, human sewage in some areas of the world, compost from garden waste such as rotted grass cuttings and mulch where plant debris is left 'in situ' on the soil surface to rot.
- **artificial fertilizers** – examples are ammonium nitrate to supply nitrogen and compound NPK fertilizers to supply nitrogen, phosphorus and potassium.

Manure is the collected faeces of farm animals, usually mixed with straw or other litter and allowed to decay for several months. When it is ploughed into the soil it provides organic matter which decays to provide the mineral salts required by plants and also forms humus which adds to the texture of soil. Dung and manure may also be buried and dispersed through the soil by dung beetles and other insects and by the action of earthworms. The proteins in the dung are acted upon by saprophytic fungi and animal digestive enzymes to yield amino acids. These are then deaminated by bacterial and fungal enzymes to yield ammonia. In the presence of oxygen the ammonia is converted to nitrates (which can be absorbed by plants) by the process of nitrification by certain bacteria.

$$NH_4^+ \xrightarrow[\text{Nitrosomonas}]{+\,O_2} NO_2^- \xrightarrow[\text{Nitrobacter}]{+\,O_2} NO_3^-$$

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Human sewage and sewage sludge, if used as a fertiliser, should be properly treated by exposure to a high temperature. Otherwise there is a danger that intestinal diseases, such as cholera, typhoid and dysentery, could be spread amongst the human population. Unfortunately, in some areas of the world the sewage is used as fertiliser without adequate pretreatment and much human disease results. In some areas in the Far East, human sewage is used to fertilize rice paddy fields.

Although small mixed farms may produce enough manure to maintain soil fertility, large arable farms, especially those practising monoculture, will not. Thus artificial fertilizers have to be used to replace soil nutrients by direct chemical means. The artificial fertilizers are produced industrially from sulphuric acid, ammonia, lime and industrial waste products. Ammonium nitrate, NH_4NO_3 is used as a source of nitrogen and ammonium sulphate, $(NH_4)_2SO_4$ supplies sulphur and nitrogen. Most artificial fertilizers contain varying proportions of nitrate, phosphate and potassium and are called NPK fertilizers. Many artificial fertilizers are particularly adapted to certain crops and soil conditions by modification of the mineral types contained and relative proportions of the different minerals within the fertilizer.

Ammonium salts for use in fertilizers are manufactured industrially by the Haber process. This uses nitrogen from the atmosphere and waste hydrogen from the petroleum industry. The gases are reacted at 550^{o}C and at a pressure of around 1000 atmospheres (101325kPa). The reaction is illustrated by the equation:

$$N_2 + 3H_2 \longrightarrow 2NH_3$$

> ***Exam hint*** *– questions testing knowledge of the mineral requirements of plants and the nitrogen cycle often also test knowledge about fertilisers, their types, uses and misuses.*

Hazards of using fertilizers

Programmes of crop rotation and careful use of farmyard manure can maintain soil fertility over long periods, even centuries, providing continual monoculture of the same crop is not practised. The organic manure contributes to the humus content of the soil and only releases minerals slowly over a long period. It helps to maintain the crumb structure, aeration and drainage of the soil, thus enhancing crop growth and the survival of the actual soil flora and fauna. However, farmyard manure should not be stored near waterways when there is a risk of nitrate leaching to the water

In comparison, the continual exclusive use of chemical fertilizers tends to lead to a loss of soil humus and thus soil crumb structure is lost, resulting in poor aeration and drainage. The eventual result is that plant roots cannot absorb oxygen for respiration and so cannot absorb salts efficiently. This results in poor crop growth and low yields.

The nitrates that are not absorbed are dissolved in rain water and washed (leached) out of the soil into ponds and lakes, streams and rivers. If excess fertilizer has also been applied, then nitrates from this also leach into waterways. Phosphates may be eroded from soils and reach waterways This over-fertilization of waterways by nitrates and phosphates is called **eutrophication** and can result in the following sequence of events:

1. the high nutrient concentration in the water enables excessive growth of algae and phytoplankton so that the water becomes congested with algal growth. This is called an 'algal bloom'.
2. the algal bloom blocks out sunlight to the aquatic plants deeper in the water. Thus these cannot survive.
3. as the algae and plants die, bacterial action causes them to decay. The decay bacteria flourish and since they are aerobic they remove oxygen from the gases dissolved in the water. This oxygen is not replaced because the photosynthesising organisms which produced it are dead.
4. the oxygen dissolved in the water becomes so depleted that fish and other aquatic animals also die. The decay of these also adds to the oxygen depletion until anaerobic conditions occur.
5. a foul-smelling anaerobic mud of semi-decayed organisms is the final result.

Leaching of phosphates into waterways has a similar effect but tends to result in blooms of blue green bacteria, such as Microcystis and Anabaena, rather than in algal blooms. The blue-green bacterial blooms release toxins which are poisonous to fish, farm animals and humans.

***Exam hint** – over-fertilization of waterways can also result from the discharge of sewage effluents into the water, particularly if they are untreated. Detergent residues in the sewage may contain high concentrations of phosphates.*
Data interpretation questions on the topic area of eutrophication are asked quite regularly.

High levels of nitrates in water intended for human consumption are linked to the development of 'blue baby syndrome'. In 'blue baby syndrome' excess nitrate taken in is converted by bacteria to nitrite in the gut. This is absorbed into the blood and combines with haemoglobin to form methaemoglobin. This cannot carry oxygen and so the baby's blood is underoxygenated and the tissues are starved of oxygen. Blood with low oxygen tension tends to be bluish-purple in colour – a symptom known as 'cyanosis'.They may also be teratogenic.

***Remember** – a teratogen is a substance that can produce fetal defects during pregnancy. A famous example is the drug 'thalidomide'.*

Remember – 'blue baby syndrome' is not the same as a 'blue baby'. A 'blue baby' results from congenital heart disease.

Excess intake of nitrates by farm animals leads to reduced vitality, increased frequency of stillbirths, low birth weights and slow weight gain.

How hazards of using chemical fertilizers may be reduced

- use fertilizers which are less soluble and so only release their nitrogen at the slowest rate compatible with enhancing crop growth.
- make more use (but not overuse) of organic manure, which conserves the humus and soil structure.
- use fertilizers which contain ammoniacal nitrogen because they leach nitrates more slowly than fertilizers which contain actual nitrates.
- tailor the application of fertilizers to the soil type – sandy type soils leach nitrates more quickly than clay type soils, which tend to retain water.
- instead of applying fertilizer in one large annual 'dose', apply it in small measures over a period of time and time these applications to coincide with the growth periods of the crop.
- the composition of chemical fertilizers can be adjusted to meet the particular requirements of specific crops so that little excess fertilizer remains in the soil after crop growth.
- do not apply fertilizers during very wet weather since high rainfall results in considerable leaching.
- public water supplies must be carefully monitored and nitrate levels lowered if they rise above permitted standards (45 ppm as nitrate). The easiest way to reduce nitrate levels is by blending the contaminated water with 'low nitrate' water.

Practice Questions

1. (a) Explain what is meant by 'eutrophication'. 2
   (b) Explain why, as a result of eutrophication:
      (i) large plants growing on the bed of a lake may die. 2
      (ii) the oxygen concentration in the water falls. 2
   (c) Explain why eutrophication may make water supplies harmful to humans. 4

2. Farmyard manure consists of a mixture of animal dung and straw.
   (a) (i) Suggest three reasons why farmyard manure is a good fertilizer. 3
      (ii) Describe how ammonium compounds liberated into soil from farmyard manure become nitrates. 3
      (iii) Why is farmyard manure less effective in waterlogged soils? 2
   (b) (i) State two advantages of using chemical fertilizers rather than farmyard manure. 2
      (ii) Describe what may happen to a soil when only chemical fertilizers are used over a long time period. 3

Answers

1. (a) excess input of nutrients into water courses/lakes/sea;
   nitrate/phosphate;
   due to leaching of NPK/nitrogenous fertilisers/detergents; max 2

   (b) (i) light penetration decreases;
   because of phytoplankton/floating algae/plants, organic matter/ turbidity increases;
   thus (deprived of light and) cannot photosynthesise; max 2

   (ii) phytoplankton/many plants die;
   are broken down by bacteria/aerobic bacteria/decomposition;
   which uses oxygen/increased BOD/biochemical oxygen demand;
   max 2

   (c) nitrates may be converted to nitrites in baby's stomach;
   nitrites reduce oxygen carrying capacity of haemoglobin;
   causing cyanosis/blue baby syndrome;
   because nitrites combine with haemoglobin forming methaemoglobin;
   nitrates may form carcinogenic nitrosamines;
   increased nitrates in water linked to higher frequency of heart disease;
   max 4

   Total 10

2. (a) (i) it is a good source of ammonium compounds/nitrates/mineral salts;
   it adds to the humus/organic matter of the soil;
   it improves the texture/crumb structure of the soil;
   (thus) it improves the aeration and drainage of the soil; max 3
   (ii) ammonium compounds oxidised to nitrites and then to nitrates;
   correct ref to Nitrosomonas; (ammonium compounds to nitrites)
   correct ref to Nitrobacter; (nitrites to nitrates) 3
   (iii) waterlogged soils contain little or no oxygen;
   Nitrosomonas and Nitrobacter/nitrifying bacteria will only operate under aerobic conditions; 2

   (b) (i) chemical fertilizers can start working immediately whereas organic manure takes time to be broken down;
   the composition of chemical fertilizers can be adjusted to suit specific crops but this cannot be done with organic manure;
   (allow other valid advantages) 2
   (ii) loss of soil humus/organic matter content;
   loss of soil texture/crumb structure;
   impaired soil drainage/waterlogging;
   loss of aeration; max 3

   Total 13

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