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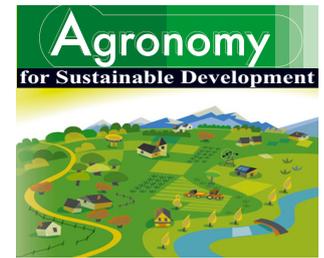
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Review article

Mineral sources of potassium for plant nutrition. A review

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Abstract – Recently published assessments of nutrient budgets on a national basis have shown that K deficits for developing countries are so substantial that a doubling of world production of potash fertilisers would be required to balance inputs and offtake, simply to meet demands in Africa alone. The price of potassium fertiliser raw materials has increased by a factor of 4 during 2007–2009, approaching \$1000 per tonne in some markets. Thus an annual investment of the order of US\$5600 million is required to replenish soil K stocks in Africa. In this context it is appropriate to review current knowledge of alternative sources of K, which is the seventh most abundant element in the Earth's continental crust, present in feldspars and (much less commonly) feldspathoid minerals including nepheline and leucite. Theoretical considerations based on the experimental determination of mineral dissolution rates indicate that nepheline dissolves 100 times more quickly than potassium feldspar, and this suggests that nepheline-bearing rocks are more effective as sources of K for plant growth than granitic rocks, even though these have higher K contents. Crop trials with silicate rocks and minerals as sources of K show increased K availability and uptake for nepheline-bearing rocks compared with granitic rocks. Under conditions where soils are rapidly leached (especially tropical soils such as oxisols that contain quartz, aluminium oxy-hydroxides and kaolinite), with low capacity to retain soluble nutrients, the use of potassium feldspar or crushed granite does give a yield response, although no greater than for conventional fertilisers. In other experiments with crushed ultramafic, basaltic and andesitic rocks improvements in crop yield are claimed, although this cannot be unambiguously related to the mineralogical or chemical composition of the rock used. In conclusion, the present high cost of conventional potassium fertilisers justifies further investigation of potassium silicate minerals and their host rocks (which in some cases include basic rocks, such as basalt) as alternative sources of K, especially for systems with highly weathered soils that lack a significant cation exchange capacity. Such soils commonly occur in developing countries, and so this approach provides an opportunity to develop indigenous silicate rock sources of K as an alternative to sometimes prohibitively expensive commercial fertilisers.

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1. INTRODUCTION

Of the three main plant nutrients, N, P and K, potassium (K) and phosphorus (P) are exclusively sourced from geological materials (Manning, 1995; van Straaten, 2007). Both nutrients are mined and processed to give fertiliser products that vary in the amount of chemical treatment involved in their preparation. Both can be used as mined (sylvinit (mixed KCl + NaCl) and phosphate rock). However, the majority of commercial phosphate fertilisers are manufactured from phosphoric acid, including composite N-P fertilisers, such as diammonium phosphate (DAP), which incorporate N as urea, ammonium or nitrate. The manufacture of nitrogen fertilisers depends largely on chemical processes that derive N from atmospheric sources or from fossil fuel materials, with subsequent energy-intensive processing to give a final product. Per unit of nutrient, N fertiliser production typically uses an order of magnitude more energy than required to produce P or K fertilisers (Lægriid et al., 1999).

World trade in fertilisers is substantial: in 2007–8, consumption is reported to be 98 million tonnes N, 40 million tonnes P (as P_2O_5), and 28 million tonnes K (as K_2O : FAO, 2008). However, trade does not necessarily reflect agricultural need, but ability to purchase. This can be demonstrated using nutrient budgets on a national and international scale, one based on trade (e.g. FAO, 2008), and the other based on scaling up farm offtakes and inputs (e.g. Sheldrick et al., 2002).

In terms of the global trade in fertiliser products, the Food and Agriculture Organisation of the United Nations (FAO, 2008) indicates that global supply of fertilisers is sufficient to meet demand. For potassium, the FAO states that global demand is likely to increase annually at 2.4%, and that supply will balance demand. However, in an analysis of the regional situation, the FAO notes that only 10 of 57 African countries consume significant quantities of fertiliser of any kind. Consumption in Africa of K fertilisers is currently approximately 485 000 tonnes (2008–9), expected to increase by 2% annually, all of which has to be imported (FAO, 2008). Other regions that rely on imported K include Oceania and Asia, with the bulk of commercial supply derived from Europe and North America.

In an assessment of nutrient budgets, Sheldrick et al. (2002) describe a nutrient audit model, in which offtakes are expressed in terms of nutrients removed from the land, and inputs include fertilisers, crop residues and manures. These are then balanced and assessed on a national, regional or global scale to determine whether or not nutrient supply is balanced by inputs. Importantly, Sheldrick et al.'s (2002) work has shown that on a global basis it is not phosphorus supply that is of most concern, but supply of potassium, with an annual global deficit of 20 kg K ha^{-1} . In an assessment of nutrient audits for Africa, Sheldrick and Lingard (2004) have shown that overall, and in most African countries, nutrient depletion has increased since 1961, with annual deficits in 1998 of 3.5 million tonnes of N ($17.4 \text{ kg N ha}^{-1} \text{ year}^{-1}$), 0.7 million tonnes of P ($3.3 \text{ kg P ha}^{-1} \text{ year}^{-1}$) and 4.1 million tonnes of K ($20.0 \text{ kg K ha}^{-1} \text{ year}^{-1}$). The highest nutrient depletion rates are for potassium.

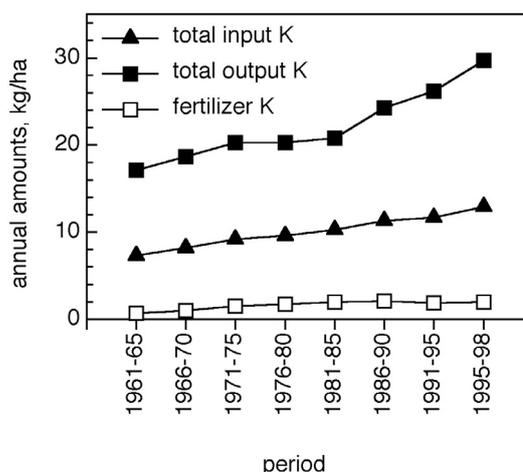


Figure 1. Potassium inputs and outputs combined for all African countries for the latter part of the 20th Century (Sheldrick and Lingard, 2004).

Using data from Sheldrick and Lingard (2004) for African countries, Figure 1 shows the extent of the imbalance between the supply and offtake of K. Between 1961 and 1998, the total output of K through offtakes has almost doubled, to $30 \text{ kg K ha}^{-1} \text{ year}^{-1}$. In contrast, fertiliser K input has remained very low, at $2.1 \text{ kg K ha}^{-1} \text{ year}^{-1}$ or less, whilst other inputs (from crop residues and manures) have increased. Potassium fertilisers make up 10% or less of the total K input, and this proportion has declined between 1961 and 1998.

The nutrient deficits identified by Sheldrick and Lingard (2004) and the problems of fertiliser supply identified by the FAO (FAO, 2008) for Africa have major implications for the supply of potash to agriculture, more widely within the developing world. This is because potash ores have a rather limited distribution globally (Rittenhouse, 1979; Moores, 2009b), with the bulk of the world's potash mined in Canada, Europe and the Middle East. Thus there is currently very little scope for many developing countries to be self-sufficient in potash using conventional fertilisers.

Furthermore, consideration of trade in the context of geographical factors, infrastructure and transport costs confirms, for example, that many (but by no means all) African countries do not compete on a level playing field with more developed countries. Limão and Venables (2001) carried out a detailed analysis using gravity modelling to assess the impact of a number of variables on the costs of trade. For sub-Saharan African countries, transport costs between countries are 136% higher than for trade between other African countries, and infrastructure costs account for half of this figure. Poor infrastructure plays a highly significant part in inhibiting trade within Africa, including transit from coastal ports to landlocked countries (Longo and Sekkat, 2004; Limão and Venables, 2001).

Focusing on potash fertilisers, and considering the situation in Africa, Figure 2 shows the amount of muriate of potash that would be needed to compensate for potassium offtake for the period shown in Figure 1. Figure 2 shows that in 1961 inputs from fertilisers equivalent to 3 million tonnes of KCl

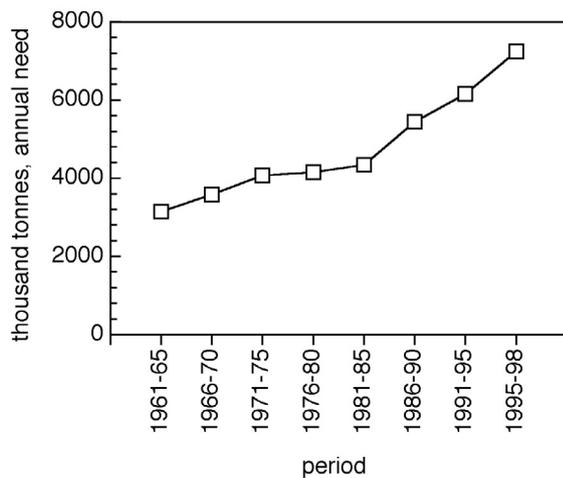


Figure 2. Estimated total requirement of K for African countries, based on difference between outputs and existing inputs.

were required to balance potassium offtake, rising to 7 million tonnes annually for the period 1995–1998. This is 70% of the annual consumption of muriate of potash by the United States during the same period (10 million tonnes per annum; Searls, 2000), and about 20% of world consumption at that time. Assuming that demand for K in Africa has not increased since 1998, the value of the annual fertiliser need for Africa identified in this way is of the order of US\$5600 million using prices for the end of 2008, likely to be an underestimate given that demand is expected to have increased since 2000.

The situation described above concerns an entire diverse continent, and varies from one African country to another. But similar deficits occur elsewhere: for 1998, China has a K deficit of 60 kg K ha⁻¹ year⁻¹, or a requirement of 8.3 million tonnes per year. To maintain this deficit and to feed its growing population, Sheldrick et al. (2003) consider that China needs to see growth in K fertiliser use at an annual rate of 8%. According to the FAO, East Asia's K deficit is in excess of 9 million tonnes per year, dominated by China (FAO, 2008). In contrast to the developing world, the USA and Europe have no potash deficit; in general, developed countries add K well in excess of offtake.

Using figures from Sheldrick et al. (2002) for the end of the 20th century, globally, there is a deficit of 20 kg K ha⁻¹ year⁻¹, corresponding to an annual global fertiliser need of 30 million tonnes of K. This corresponds to a requirement for an additional 60 million tonnes of KCl (35 million tonnes of K₂O equivalent), which is slightly greater in quantity than the most recent published estimates of current world production (approx. 30 million tonnes of K₂O equivalent; Ober, 2007).

Thus to satisfy demand from world crop production for K, the amount of additional potash required is equivalent to slightly more than current global mined production. Production and consumption of potash fertilisers must more than double to sustain soil K stocks. At present, the potassium deficit that arises from offtake of crops is being supplied by the soils. Using K as an indicator of other mineral-derived nutrients, it

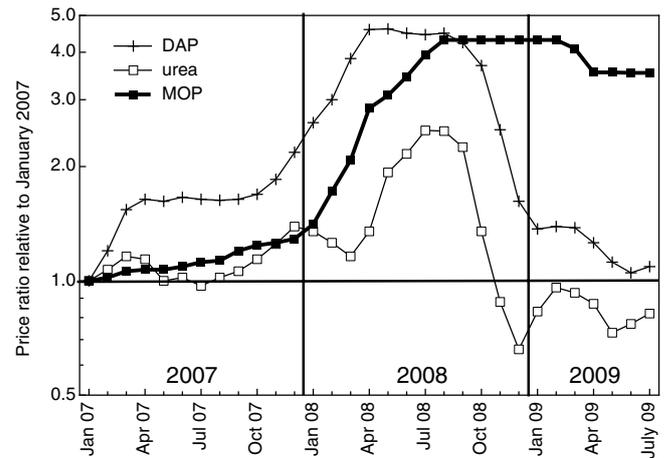


Figure 3. Changes in prices to July 2009 of muriate of potash (MOP), urea and diammonium phosphate (DAP) fertilizers, relative to January 2007 prices (calculated using data from ICIS; <http://www.icis.com>).

appears that global agricultural production is responsible for nutrient mining on a huge and evidently unsustainable scale.

The above review of Sheldrick's work is based on nutrient balances for the late 20th Century. The first decade of the 21st Century has seen the growth of China as an industrial power, with concomitant demand for natural resources, including fertilisers. This has led to substantial demand for K, and world prices have risen accordingly.

Figure 3 compares changes in price (not corrected for inflation) for three fertilisers since the start of 2007: urea, diammonium phosphate (DAP) and muriate of potash (MOP). For N and P fertilisers, it clearly shows an increase and subsequent decrease that coincides broadly with trends in oil prices that occurred in the latter part of 2008, reflecting the close links between these and the fossil fuel industry. Prices for these fertilisers return to values similar to those of January 2007 (DAP; approximately US\$ 280/tonne compared with US\$ 250/tonne in January 2007) or are lower (urea; approximately US\$ 280/tonne compared with US\$ 350/tonne in January 2007). In contrast, the price of potash (muriate of potash, price Freight On Board (FOB) Saskatchewan) for the period rose by a factor of 4 in this period, from US\$180/tonne to US\$650/tonne, with a peak price of US\$ 800/tonne for much of late 2008, and spot market prices of US\$1000/tonne reported on the internet. Most importantly, the price of K has not decreased in parallel with the observed decrease in price of N and P fertilisers. This observation is discussed in more detail by Moores (2009a, b), and fundamentally distinguishes potash fertilisers. The high price of potash reflects factors in addition to those associated with manufacture, including inability of supply to keep pace with demand.

Given the apparent obstacles to trade and the high cost of potash, it is important to consider how the African potash deficit identified by Sheldrick and Lingard (2004) can be addressed. One possibility is to identify new sources of K.

Table I. Chemical formulae and potassium contents (expressed as element and oxide) for potash ore minerals and for common potassium silicate rock forming minerals.

Mineral	Formula	Weight % K	Weight % K ₂ O
<i>Potash ore minerals</i>			
Sylvite	KCl	52.35	63.09
Carnallite	MgCl ₂ .KCl.6H ₂ O	14.05	16.94
Kainite	KMgSO ₄ Cl.3H ₂ O	15.69	18.91
Langbeinite	2MgSO ₄ .K ₂ SO ₄	18.84	22.71
<i>Silicate minerals</i>			
Potassium feldspar	KAlSi ₃ O ₈	14.03	16.91
Leucite	KAlSi ₂ O ₆	17.89	21.56
Nepheline	(Na,K)AlSi ₃ O ₈	13.00	15.67
Kalsilite	KAlSiO ₄	24.68	29.75
Muscovite	KAl ₃ Si ₃ O ₁₀ (OH) ₂	9.03	10.88
Biotite	K ₂ Fe ₆ Si ₆ Al ₂ O ₂₀ (OH) ₄	7.62	9.18
Phlogopite	K ₂ Mg ₆ Si ₆ Al ₂ O ₂₀ (OH) ₄	9.38	11.30

There are known deposits of potash salts (e.g. Republic of Congo, De Ruiter, 1979; Thailand, El Tabakh et al., 1999) that presently are not mined. The Republic of Congo deposits (located 16 km east of the port of Pointe-Noire) are (according to internet sources) at an advanced stage of mine planning and may represent a significant source in due course. However, in general the distribution of conventional mined potash salts has changed little since Rittenhouse (1979) considered global supply and demand, and is unlikely to change given the very substantial cost of developing a producing mine (US\$2000 million; Moores, 2009b). In any case, given the difficulties of intra-African trade (Limão and Venables, 2001), the possible development of the Pointe-Noire potash deposits is unlikely to improve the availability of K in those countries that most need it, especially as the products of the mine are likely to be sold on the world market at a similar price to those from other sources.

In these circumstances it is appropriate to consider the availability of K within soil systems from first principles, and to consider unconventional sources of K that are not necessarily attractive on a commercial basis to the global fertiliser industry but that might be appropriate in circumstances where farmers are presently excluded from global fertiliser markets.

In soil systems, retention of potassium is wholly dependent on the cation exchange capacity of the soil. This, in turn, is largely controlled by the presence within soils of predominantly clay minerals that have an interlayer site capable of accommodating K, such as the illite group or vermiculites (Sposito, 1989). In two of the major soil orders, oxisols and ultisols, cation exchange capacity is very low, reflecting the leaching from these of cations as a consequence of the extreme weathering process that they have undergone. Such soils are characterized by the presence of quartz, kaolinite and Fe-Al oxy-hydroxides, representing a residual mineral assemblage from which nutrients such as K have been leached. These soils occur widely in tropical areas of Africa, South America and Australia. Their cultivation requires addition of nutrients including K, which are removed by through drainage as well as by plant uptake.

For an agricultural system in a poor country in which oxisols dominate, the supply of K is a critical limiting factor. In this context it is appropriate to consider unconventional geological sources of K that, whilst less effective than the soluble salts that make up commercial fertiliser products, are widely available globally and might be expected to weather rapidly within a soil, releasing sufficient K to provide agronomic benefit. Such sources include silicate rocks, whose use as a source of plant nutrients has been discussed by a number of authors (van Straaten, 2006, 2007; Leonardos et al., 1987; Harley and Gilkes, 2000; Gillman et al., 2002).

The purpose of this review is first to present the theoretical background that justifies the use of crushed silicate rocks as a source of plant nutrients, focusing on K, and secondly to provide an overview of the results of existing published trials using crushed rocks as an alternative to conventional fertilisers. It then considers in principle whether or not crushed silicate rocks should be considered as one source of K that can address deficits on a basis that is appropriate for sustainable crop production, and highlights the need for strategic and consistent future trials.

2. MINERAL SOURCES OF K

In the context of meeting the world's need for potash fertilisers, there is no doubt that conventional soluble salts will continue to dominate in developed countries. Table I lists the principle potash fertiliser ore minerals, together with the dominant rock-forming potassium silicate minerals. In natural soils, potassium is derived ultimately from the potassium silicate minerals, which can be subdivided into those that are formed at high temperatures by igneous and metamorphic processes (feldspars and feldspathoids; primary micas), and those that are produced on weathering of the high-temperature minerals (clay minerals, especially illite). In deeply weathered, highly oxidized soils that have low organic matter, it is essentially the clay minerals that are responsible for the exchangeable K that is measured in soil analysis; the high temperature silicate minerals provide a reservoir of fixed K.

Table II. Weathering reactions for framework aluminosilicate minerals (Curtis, 1976).

	Reaction	ΔG_r , kJ/mol	ΔG_r , kJ/ gram atom
Ks	$2\text{KAlSiO}_4 + 2\text{H}^+ + \text{H}_2\text{O} = 2\text{K}^+ + \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	-115.25	-6.07
An	$\text{CaAl}_2\text{Si}_2\text{O}_8 + 2\text{H}^+ + \text{H}_2\text{O} = \text{Ca}^{2+} + \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	-98.49	-5.47
Ne	$2\text{NaAlSiO}_4 + 2\text{H}^+ + \text{H}_2\text{O} = 2\text{Na}^+ + \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	-91.02	-4.79
Lc	$2\text{KAlSi}_2\text{O}_6 + 2\text{H}^+ + \text{H}_2\text{O} = 2\text{K}^+ + \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 + 2\text{SiO}_2$	-88.00	-3.52
Ab	$2\text{NaAlSi}_3\text{O}_8 + 2\text{H}^+ + \text{H}_2\text{O} = 2\text{Na}^+ + \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 + 4\text{SiO}_2$	-87.74	-2.83
Mc	$2\text{KAlSi}_3\text{O}_8 + 2\text{H}^+ + \text{H}_2\text{O} = 2\text{K}^+ + \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 + 4\text{SiO}_2$	-67.70	-2.18

It is normally assumed that the weathering of the feldspars and feldspathoids is very slow, and that their addition to soil will not be beneficial for crop growth, especially when compared with conventional potash fertilisers, which, being salts, are readily soluble as well as having high K contents. A number of studies have investigated silicate rocks as sources of K (and other nutrients), in response to the following drivers:

- (1) nutrient supply for organic farmers, principally in developed countries, who seek an alternative to salts (partly in response to environmental protection demands). This is in part related to the 'Remineralise the Earth' philosophy of plant nutrition using rock dust (<http://remineralize.org>);
- (2) nutrient supply for farmers in developing countries who lack funds to purchase conventional fertilisers.

Both areas of application have shown that in some circumstances potassium silicate rocks can act as effective sources of K, with long term crop yields that meet the needs of the producer. A number of commercial enterprises use potassium silicate rocks in long-standing businesses with satisfied customers, particularly in the organic farming sector (e.g. <http://www.glensideorganics.co.uk>). However, the scientific evidence for the possible agronomic value of potassium silicate rocks is dispersed in a number of publications, and these do not generally refer to specific commercial products.

3. THE POTASSIUM ALUMINIUM SILICATE MINERALS: STABILITY AND DISSOLUTION RATES

Potassium occurs as an essential component within the feldspars and feldspathoid mineral groups. In both groups, the mineral structure is a three dimensional network of silica tetrahedra, in which substitution of Al for Si leads to a charge deficiency that is balanced by the presence of Na^+ , K^+ or Ca^{++} . The potassic aluminosilicate minerals and their formulae are summarised in Table I, which also gives their theoretical K_2O contents, ranging from 18–30 wt% (equivalent to 15–25 wt%; 150–250 g kg^{-1} K). Of the aluminosilicate minerals, potassium feldspar is most commonly found, occurring in a wide range of rock types (granite, sandstone, gneisses, etc). Orthoclase (Or) and microcline (Mc) are common varieties of potassium feldspar, differing in their crystal structure (Deer et al., 1992). Leucite (Lc), nepheline (Ne) and kalsilite (Ks) are much less widely distributed, predominantly occurring in

nepheline syenites and related volcanic rocks, and some alkaline basalts. Nepheline is relatively readily available as a commodity, as it is mined as a raw material for ceramic and glass manufacture. End-member nepheline is a sodium aluminium silicate; natural nepheline typically contains potassium to the extent of 20% of the cation site. Leucite and kalsilite are not readily available as commodities, and often occur mixed with secondary products of their weathering and alteration.

The thermodynamic stability of the potassium aluminium silicates can be assessed using the approach of Curtis (1976). A balanced chemical reaction can be written in which aluminium is conserved and the weathering products include mineral phases that are known to be stable under Earth-surface conditions. This approach provides a thermodynamic basis for empirical stability series such as that produced by Goldich (1938; Curtis, 1976). Table II shows the reactions for the aluminosilicates, including the plagioclase feldspars anorthite (An) and albite (Ab) for comparison. The calculated free energy changes for the reactions are given in Table II, taking into account variation in the written formula by expressing the free energy change per gram atom rather than per mole (this approach allows comparison of like with like in terms of the numbers of bonds being broken as the framework silicate weathers; Curtis, 1976). The least stable mineral is kalsilite, followed by nepheline, then leucite and finally potassium feldspar (microcline). On the basis of these thermodynamic data, kalsilite and nepheline stabilities are similar to those of the calcic plagioclase feldspars.

In addition to variation in their thermodynamic stability, the potassium aluminosilicates vary in the kinetics of their dissolution reactions. Data for these are available for the feldspars (summarised by Blum and Stillings, 1995) and for nepheline (Tole et al., 1986); there are no comparable dissolution rate data for leucite or kalsilite. Dissolution of the aluminosilicates takes place as a consequence of hydrolysis reactions at the mineral surface (Brantley and Stillings, 1996); these reactions are irreversible. They liberate cations to the solution and disrupt the framework structure of the mineral. Thus they differ fundamentally from the reversible cation exchange reactions that characterise the interlayer site of the clays and micas and the exchange site of the zeolites.

The available dissolution rate data for the feldspars and for nepheline are given in Table III. It is important to compare corresponding experimental conditions, as a wide range of temperatures, pH and other factors has been considered in kinetic studies. Blum and Stillings' review (1995) assembles directly comparable information in one source. It is also important to

Table III. Dissolution rates for potassium silicate minerals and other feldspars (date from Blum and Stillings, 1995).

Mineral	Dissolution rate Log k+	Relative dissolution rate
Potassium feldspar	-9.93 (pH 1-5.7)	1.9
	-10.2 (basic)	1
Leucite	Not known	-
Nepheline	-8.2 (pH5)	100
	-8.6 (pH7)	40
Kalsilite	Not known	-
Anorthite	-5.87	21000
Albite	-9.69	3.2

note that these experimentally-determined dissolution rates are not directly applicable to the soil environment (e.g. White, 1995). Of particular importance is the experimental difficulty in determining the reacting surface area of the mineral. The feldspars (and presumably the feldspathoids) characteristically are riddled with holes and structural defects at a very fine (molecular) scale (Lee and Parsons, 1995), and these can have a major effect on dissolution kinetics.

Table III also shows relative dissolution rate data for the potassium aluminosilicates, albite and anorthite. Dissolution rates vary according to pH; for comparable pH values, nepheline's dissolution rate exceeds that of potassium feldspar by as much as 100 times. Because of its lower thermodynamic stability compared with nepheline, it might be predicted that kalsilite has a higher dissolution rate, although its similar framework structure means that its dissolution rate is likely to be similar to that of nepheline. Leucite is expected to have a dissolution rate that is intermediate between nepheline and potassium feldspar.

4. POTASSIUM IN SILICATE ROCKS

The potassium silicate minerals typically occur mixed with other silicate minerals, and this dilutes the K content. In general terms, K is the seventh most abundant element in the Earth's continental crust, the composition of which is dominated by rocks of granitic composition and the products of their weathering and erosion. Potassium feldspar is an essential component of granitic rocks, which also contain the micas biotite and muscovite. Weathering of granitic rocks initially produces secondary muscovite and chemically-similar illitic clays, and if conditions are right ultimately produces the potassium-free clay mineral kaolinite.

Although potassium feldspar, muscovite and biotite are very common, the other potassium silicate minerals are rare. Nepheline occurs in very specific igneous rock types that occur sporadically, mainly as intrusive rocks but also within lavas. Kalsilite and leucite both occur mainly in volcanic rocks (Deer et al., 1992), in potassium-rich lavas from specific regions. These include rift valleys, such as the East African Rift (Woolley, 2001).

Examples of typical rock compositions are given in Table IV. This table also shows estimated compositions for the

upper continental crust, based on the observed composition of till derived from glacial erosion of (a) igneous rocks and (b) sedimentary (Carboniferous) sequences. Table IV also gives the composition of particulates carried by the Ganges, which contribute nutrients to soils when deposited in annual floods. Table IV shows that the potassium content of some readily available, and some rare, rock materials are quite similar, ranging from 2.7–5.6 wt% K₂O.

Table IV also recalculates the composition of the rock or sediment in terms of the equivalent hypothetical, normative, content of orthoclase (K-feldspar), nepheline and leucite. The normative composition shows that glacial sediments derived from granitic terrains are chemically very similar (in terms of K content) to their source, justifying consideration of the use of tills of this type for soil remineralisation. However, glacial till can be highly variable in composition (Barlow, 1996), its composition reflecting mixing between different mineral components within the substrate. Thus the samples reported by Barlow (1996) show mixing between quartz (derived from sandstone) and a clay-rich fraction derived from mudstones. Tills derived from sedimentary rocks may have lower K contents, and lower normative orthoclase, as a consequence of weathering prior to till formation.

5. EVIDENCE OF SILICATE MINERALS AS SOURCES OF K

A number of studies have addressed the ability of different potassium silicate minerals to yield nutrients under laboratory and pot trial conditions.

The ability of feldspar to dissolve in soil conditions, yielding K, has been determined by Riggs et al. (1993). Potassium feldspar was added to soil and subjected to leaching and incubation experiments. These showed that feldspar leaching was effective in open system leaching experiments, more so than in closed-system incubations. Similarly, Blum et al. (1989) compare a number of different rock types as sources of mineral plant nutrients. Assuming that micas and feldspars are concentrated in the silt and sand fractions of a soil, Mengel et al. (1998) compared the extractable K contents and the performance of ryegrass (*Lolium perenne*) for whole soil and for the same soil from which the clay fraction had been removed. Finding no difference between the two soils, Mengel et al. (1998) conclude that K is as easily available from the sand and silt fraction as from the whole soil. In earlier trials with soils that differ in their sand, silt and clay content (again with no detailed mineralogical or geochemical analysis), Mengel and Rahmatullah (1994) observed potassium deficiency in wheat (*Triticum aestivum* cv. Faisalabad 83), maize (*Zea mays* L. cv Gohar) and barley (*Hordeum vulgare*), but adequate K nutrition of elephant grass (*Pennisetum purpureum*).

The interaction between silicate minerals and microbial systems has been investigated by a number of authors. In the context of fungal community development on natural weathered rock surfaces, Gleeson et al. (2005) show that individual minerals are associated with distinct fungal community structures that relate to the chemical composition of the mineral.

Table IV. Typical compositions of igneous rocks (Le Maitre, 1976) and estimates for continental crustal composition based on till and suspended sediment composition (Goldschmidt, 1933; Rudnick and Gao, 2003; Martin and Meybeck, 1979).

	Granite	Trachyte	Diorite	Nepheline syenite	Basalt	Nephelinite	Upper continental crust (glacial sediments)	Glacial till (clay-rich)	Ganges river particulates
<i>Comments:</i>	Common	Rare	Moderately common	Rare	Common	Very rare	Igneous/ Metamorphic crust	Sedimentary rock source	
Oxide									
SiO ₂	71.30	61.21	57.48	54.99	49.20	40.60	62.22	79.31	66.9
TiO ₂	0.31	0.70	0.95	0.60	1.84	2.66	0.83	0.39	0.96
Al ₂ O ₃	14.32	16.96	16.67	20.96	15.74	14.33	16.63	7.54	16.0
Fe ₂ O ₃	1.21	2.99	2.50	2.25	3.79	5.48	–	–	–
FeO	1.64	2.29	4.92	2.05	7.13	6.17	6.99*	3.21*	5.2*
MnO	0.05	0.15	0.12	0.15	0.20	0.26	0.12	0.05	0.14
MgO	0.71	0.93	3.71	0.77	6.73	6.39	3.47	1.11	2.3
CaO	1.84	2.34	6.58	2.31	9.47	11.89	3.23	1.16	4.1
Na ₂ O	3.68	5.47	3.54	8.23	2.91	4.79	2.15	0.57	1.5
K ₂ O	4.07	4.98	1.76	5.58	1.10	3.46	4.13	1.74	2.7
P ₂ O ₅	0.12	0.21	0.29	0.13	0.35	1.07	0.23	0.09	–
Normative potassic minerals									
Or	24.50	29.41	10.42	32.98	6.53	3.16	24.41	10.28	15.96
Lc	–	–	–	–	–	13.57	–	–	–
Ne	–	–	–	21.77	–	21.95	–	–	–

Similarly, Rosling et al. (2004) showed that eight different ectomycorrhizal fungal cultures responded differently to culturing in the presence of minerals (quartz, apatite, potassium feldspar and marble).

In laboratory experiments in which the fungus *Aspergillus fumigatus* was applied to a potassium-rich shale (containing principally K-feldspar), K release was enhanced by two orders of magnitude (Lian et al., 2008). In addition to the role played by organic acids exuded by the fungus, Lian et al. (2008) observed increased K yields when the organism was in contact with the mineral substrate, suggesting that surface interactions, some of which are mechanical, enhance K release.

Wallander and Wickman (1999) compared ectomycorrhizal and non-mycorrhizal cultivation of *Pinus sylvestris* seedlings in pot trials where the source of K was potassium feldspar (microcline) or biotite. In both cases, release of K from the minerals (as measured by biomass K contents) was enhanced by the presence of mycorrhizal fungi.

6. USE OF POTASSIUM-BEARING SILICATE ROCKS AS A FERTILISER

Proposals to use potassium silicate rocks and minerals as sources of plant nutrients are not new; Lloyd (1918) comments that it is economically not viable to extract K from silicate rocks to produce fertilisers, despite the availability of a number of different methods. Instead of regarding potassium silicate-bearing rocks as an 'ore' from which to extract K artificially, it is more appropriate to consider their direct use, allowing plants and their root processes to extract the K that they need.

Selection of a silicate rock potash fertiliser can be based on the absolute potash content, which is then tested for availability (e.g. Barral Silva et al., 2005). An alternative approach is to select on the basis of dissolution rate. The value of this approach is illustrated in Figure 4, which shows the relative rates of loss of K to solution from two silicate minerals, potassium feldspar and nepheline, at neutral pH and pH 5 over a period of 1 year, for a surface area of 1 m² g⁻¹. Figure 4 clearly shows that the release of K from nepheline, with 3.8% K, is an order of magnitude greater than release from potassium feldspar (15% K), and that this observation applies to pH values that are appropriate for manures and soil solutions influenced by active root growth. Thus rocks that contain nepheline (and by implication kalsilite and leucite) are likely to be more effective as sources of K than those that contain K-feldspar alone.

7. CROP TRIALS WITH POTASSIUM SILICATE MINERALS

Table V summarises a number of trials that have used silicate rock materials as a source of plant nutrients, focusing on K. These trials include pot (greenhouse) and field experiments, using a range of differing crops, for differing time scales and in different climates.

7.1. Trials with granite and related rocks

A consistent set of trials has been carried out in Western Australia, in which the same granite was used in field trials on wheat, and pot trials on wheat, clover and ryegrass

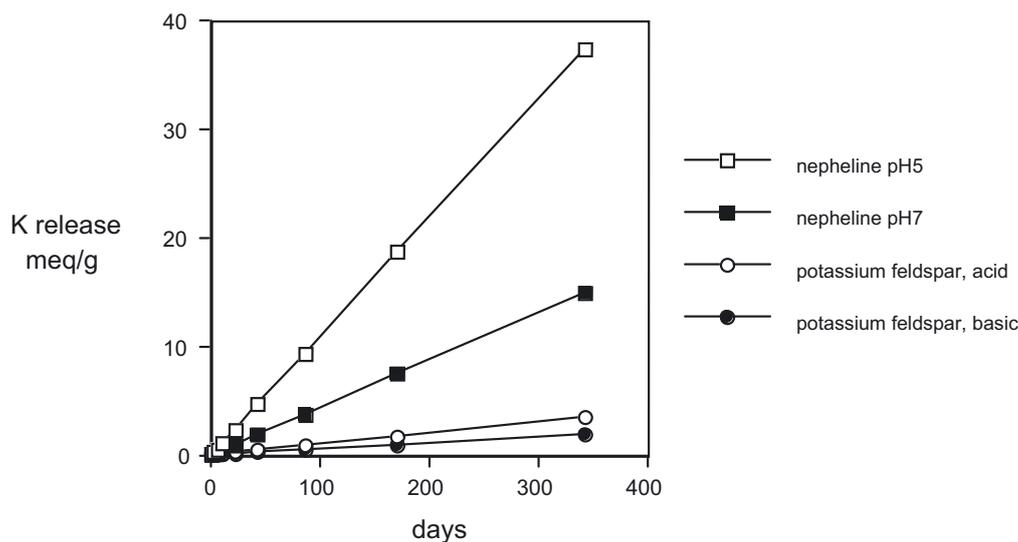


Figure 4. Release of K (expressed as milliequivalents/gram) from nepheline and potassium feldspar calculated from mineral dissolution rates.

(Coroneos et al., 1996; Hinsinger et al., 1996; Bolland and Baker, 2000). Although a consistent source of granite powder was used, the K content varied from one study to another, from 2.2–3.8% K_2O . Application rates also varied, up to the equivalent of 30 T rock per hectare (up to 1 T ha^{-1} K). Contrasting results were obtained. For pot experiments with wheat, Hinsinger et al. (1996) used granite (2.29% K_2O) and found significantly increased (by 10%–20%) biomass yields for applications of 7.5 T rock ha^{-1} (equivalent to 0.24 t $K ha^{-1}$). Experiments with ground diorite (0.3% K_2O) gave no increase in yield. Other work with wheat was inconclusive: Bolland and Baker report wheat yields for field and pot trials with applications of 2, 5 and 20 T rock per hectare (again 2.29% K_2O), with no increase in yield compared with the control. In contrast, pot trials using clover and ryegrass with the equivalent of 20 T rock per hectare (3.85% K_2O ; Coroneos et al., 1996) showed that application of granite powder did enhance both yield and shoot K content significantly compared with control. In all cases similar sandy soils with very low exchangeable K were used. From this work, it was concluded that the benefits of using crushed rock materials as a source of K are not sufficient in view of the cost differential compared with conventional soluble K sources (Harley and Gilkes, 2000). As the price of K has risen by a factor of at least 4 since 2000 (US\$ 120/tonne), this conclusion may no longer be valid.

Pot trials with gneiss, which is a highly metamorphosed rock mineralogically similar to granite, are reported by Wang et al. (2000). The mineralogical and chemical compositions of the gneiss used in these experiments are not given, apart from the K content (29.6 g $K kg^{-1}$ or 3.57% K_2O), and the observation that feldspar, muscovite and biotite are present. The purpose of the experiment was to compare the ability of different plants to extract K from the minerals within the gneiss, using maize (*Zea mays* L. cv. ND60), pak choi (*Brassica campestris* L. ssp. *chinensis*), Italian ryegrass (*Lolium multiflorum* L.), perennial ryegrass (*Lolium perenne* L.) and two alfalfa cul-

tivars (*Medicago sativa* L. cv. Asta and cv. Haifei). Dry yields were found to be similar for plants grown with gneiss compared with those supplied with a corresponding nutrient solution, but K uptake was lower for plants grown with gneiss. Comparing different grain sizes for the crushed gneiss, K uptake was greatest for finer size fractions of gneiss, and in all cases greatest for maize, then ryegrass and pak choi. Wang et al. (2000) conclude that plant growth facilitates the release of K from gneiss, which contains the potassium minerals feldspar, muscovite and biotite, with varying efficiency that relates to root biomass and root activity.

7.2. Trials with nepheline-bearing rocks and mineral residues

To compare the possible effects of different potassium-bearing silicate minerals, studies reported by Bakken et al. (1997 and 2000) present data for experiments involving (a) Italian ryegrass (*Lolium multiflorum italicum* var. Turilo) in pot trials (Bakken et al., 1997) and (b) the growth of a mixture of timothy (*Phleum pratense* L.) and meadow fescue (*Festuca pratensis* L.) in field trials in central and northern Norway (Bakken et al., 2000). The sources of potash were mine tailings (nepheline-bearing carbonatites (an igneous carbonate rock); nepheline syenites), a quarried epidote schist, and commercial products (adularia shale, biotite concentrate). All K sources, including KCl for comparison, were applied at the rate of 50 $kg K ha^{-1}$ in the first and second years only. Over a three year period, dry yield and K offtake were determined.

In their analysis of the results from these trials, Bakken et al. (2000) note that dry yields with KCl application were greatly in excess of those for the rock applications for years 1 and 2, but insignificantly different for year 3. Treatments with feldspar-rich rocks did not differ significantly from control, but those with biotite and nepheline-bearing rocks did show increased dry yields. However, in pot trials, Bakken et al. (1997)

Table V. Summary of trials with silicate rocks as nutrient sources (K). Ksp: potassium feldspar; Ne: nepheline; Bi: biotite.

Crop	Species/cultivar (where stated)	Mineral/rock	Trial type	Duration (months)	Agronomic benefits	Reference
Alfalfa	<i>Medicago sativa</i> L. cv Asta and cv Haifei	Gneiss	Pot	1.75	Insignificant	Wang et al., 2000
Clover	<i>Trifolium subterraneum</i>	Granite	Field/pot	12/1-1.5	Insignificant	Bolland and Baker, 2000
Clover	<i>Trifolium subterraneum</i> cv Trikkala	Granite	Pot	5	Increased yield and K uptake	Coroneos et al., 1996
Grass	Timothy <i>Phleum pratense</i> L., Meadow fescue <i>Festuca protense</i> L.	Ksp and Ne+Bi-rich mine tailings	Field	36	K uptake similar for Ne-bearing tailings and KCl; Ksp-hosted K inadequately available.	Bakken et al., 2000
Grass	<i>Brachiaria dictioneura</i>	Feldspar (Ksp)	Field	14	Insignificant	Sanz-Scovino and Rowell, 1988
Grass	Italian ryegrass <i>Lolium multiflorum</i> L.	Gneiss	Pot	1.75	Significant K mobilization	Wang et al., 2000
Grass	Perennial ryegrass <i>Lolium perenne</i> L.	Gneiss	Pot	1.75	Significant K mobilization	Wang et al., 2000
Grass	Rye grass <i>Lolium rigidum</i> cv Standard	Granite	Pot	5	Increased yield and K uptake	Coroneos et al., 1996
Italian ryegrass	<i>Lolium multiflorum italicum</i> var . Turilo	Ksp and Ne+Bi-rich mine tailings	Pot	6	Ksp-hosted K inadequately available. Increased yield for Bi and Ne-bearing rocks.	Bakken et al., 1997
Legume	<i>Pueraria phaseoloides</i>	Feldspar (Ksp)	Field	14	Insignificant	Sanz-Scovino and Rowell, 1988
Maize	<i>Zea mays</i> l. cv ND60	Gneiss	Pot	1.75	Significant K mobilization	Wang et al., 2000
Okra	<i>Abelmoschus esculentus</i> cv Eskandrani and cv Balady	Feldspar (Ksp)	Field	24	Increased pod yield compared with conventional fertiliser	Abdel Mouty and El-Greadily, 2008
Onions	<i>Allium cepa</i> , L.	Feldspar (Ksp)	Field	24	15% less yield than equivalent chemical fertiliser	Ali and Tallab, 2008
Pak choi	<i>Brassica campestris</i> L. ssp. <i>Chinensis</i> L.	Gneiss	Pot	1.75	Significant K mobilization	Wang et al., 2000
Rice	<i>Oryza</i> sp.	Phlogopite	Pot		Increased grain yield	Weerasuriya et al., 1993
Spruce	<i>Picea</i> sp.	Phonolite	Field	60	Increased uptake	Von Wilpert and Lukes, 2003
Tomatoes	<i>Solanum lycopersicum</i> : variety not stated	Feldspar (Ksp)	Field	12	Increased yield	Badr, 2006
Wheat	<i>Triticum aestivum</i>	Granite	Field/pot	12/1–1.5	Insignificant	Bolland and Baker, 2000
Wheat	<i>Triticum aestivum</i> cv Gutha	Granite	Pot	2.5	Increased yield	Hinsinger et al., 1996
Wheat	<i>Triticum aestivum</i> cv Gutha	Diorite	Pot	2.5	Insignificant	Hinsinger et al., 1996

note that K uptake is similar for applications of nepheline-bearing carbonatite fines and KCl, and that results for experiments with K feldspar gave similar uptake to controls.

Figure 5 illustrates the different performance of the minerals used in Bakken et al.'s (2000) trials. In Figure 5, the relative contributions of potassium feldspar, nepheline and biotite to the potassium content of the rock are expressed as an index (K-feldspar index = %K-feldspar/(%K-feldspar+%nepheline+%biotite), etc.) that allows the different rock types to be compared. These figures

show that in general there is an increase in yield, compared with control, as the proportions of both nepheline and biotite increase. The zero nepheline index samples include the control and results for trials with 100% biotite. Because these figures concern relative proportions of the three minerals, the apparent decline in yield with increasing K-feldspar index (Fig. 5a) reflects the decreasing proportion of either nepheline or biotite.

A related trial with potentially nepheline-bearing rock is reported by von Wilpert and Lukes (2003), who used phonolite from the German Kaiserstuhl carbonatite complex in

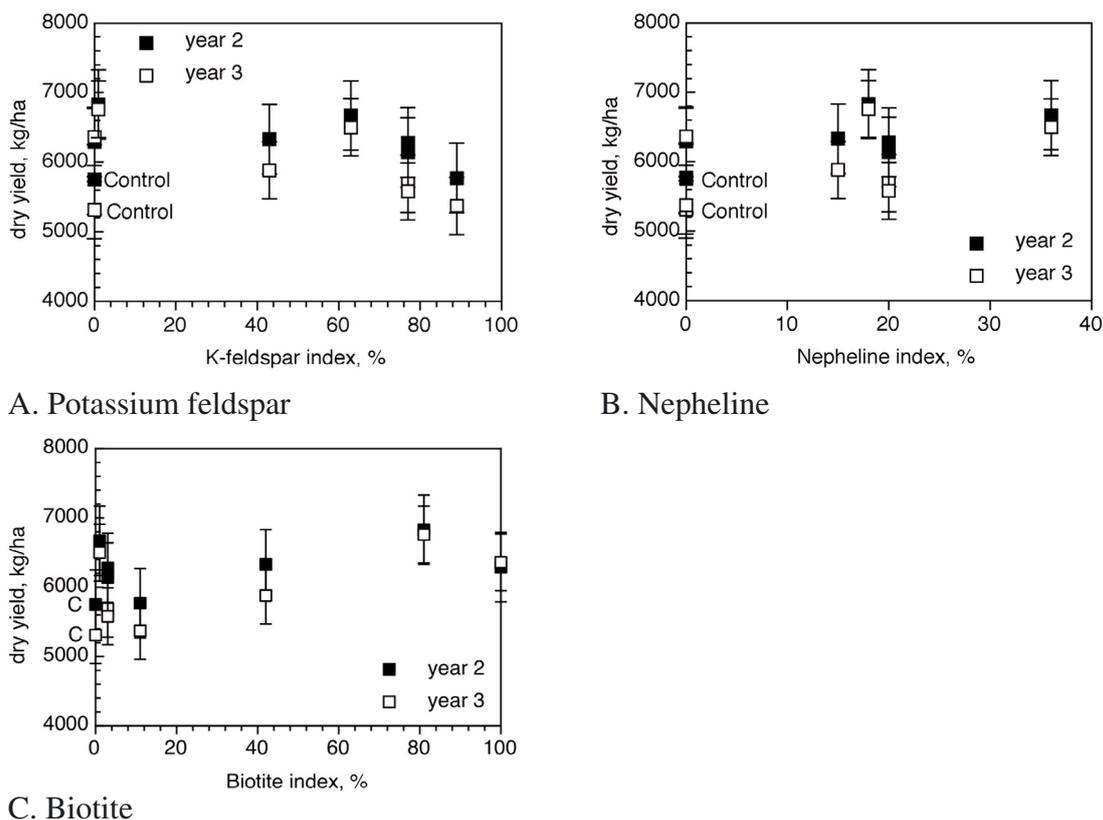


Figure 5. Comparison of the performance of rock types used by Bakken et al. (2000) on the basis of their relative proportions of potassium feldspar, nepheline and biotite.

experiments with spruce (*Picea* sp.) on a glacial loam. Although the detailed mineralogy and origin of the phonolite is not given, in the context of published descriptions of phonolites from this location it can be assumed that if correctly named it contains nepheline (a characteristic of this rock type). Von Wilpert and Lukes (2003) report that the phonolite used in their trials contains 4.23% K (5.1% K_2O), and that the rock may have contained zeolite minerals (giving it enhanced cation exchange capacity). The trials compared dolomite, phonolite and potassium sulphate, and showed that after 5 years the application of the two rock powders had influenced soil properties measurably, with an increase in the exchangeable ion pool. Nutritional effects were determined from the K content of the spruce needles, which after 4 years increased with the application of phonolite (but still remained below the deficiency threshold). Application of potassium sulphate eliminated the potassium deficiency, but led to deficiency in Ca and Mg, and had no major effect on soil properties. The value of phonolite as a long term source of nutrition was questioned in terms of an observed release of sodium, but the rock used in this trial was unusually rich in sodium for a phonolite (4.37% Na; 5.9% Na_2O); other phonolites, or related trachytes (which can be extremely K rich, up to 12–13% K_2O ; e.g. Sutherland, 1967) may not have this problem.

In a separate study involving pot trials with rice (*Oryza* sp.), Weerasuriya et al. (1993) used phlogopite mica (a magnesium

equivalent to biotite, in which Fe is substituted entirely by Mg; Deer et al., 1992) and potassium feldspar, both treated with concentrated nitric acid to enhance the availability of K. Application rates were equivalent to 200 $kg\ ha^{-1}$ for phlogopite and 500 $kg\ ha^{-1}$ for feldspar, corresponding to approximately 10 $kg\ K\ ha^{-1}$ as total K. Significant increases in rice yield (panicle number and seed weight) were observed for the use of phlogopite compared with both control and muriate of potash.

7.3. Trials with feldspars

Other work with feldspars alone has been carried out in Egypt, in field trials with okra (Abdel-Mouty and El-Greadly, 2008), onions (Ali and Taalab, 2008) and tomatoes (Badr, 2006). In trials with okra (*Abelmoschus esculentus* cv Eskandrani and cv Balady), potassium feldspar was used as one of a number of treatments designed to assess crop response (Abdel-Mouty and El-Greadly, 2008). Significant increases in pod yield were observed in treatments with potassium feldspar compared with a control, and these increases were enhanced with foliar application of gibberellic acid.

Similarly, Ali and Taalab (2008) report increasing individual bulb weight for onions (*Allium cepa* L.) with increasing feldspar application, and increasing overall yield, from 18 $T\ ha^{-1}$ with application equivalent to 95 $kg\ K\ ha^{-1}$, to

30 T ha⁻¹ with 285 kg K ha⁻¹. Crop yields were however lower than those recorded for equivalent chemical fertiliser applications, by about 15%.

In experiments with mixtures of compost and feldspars, Badr (2006) reports an increase in the amount of available K with increasing proportions of added feldspar. There was also a clear increase in tomato yield with increasing proportions of feldspar in the composts used, from yields of 27 t/ha (control) to 45 T ha⁻¹ with an application equivalent to 360 kg K ha⁻¹. Potassium content of fruits also increased. Again, fruit yields were 10–15% less than observed for application of chemical fertiliser (in this case potassium sulphate).

The Egyptian experiments with potassium feldspars suggest that feldspar is almost as effective as a soluble potash fertiliser. Sanz-Scovino and Rowell (1988) report trials with a mix of the grass *Brachiaria dystioneura* and the legume *Pueraria phaseoloides* with the potassium feldspar sanidine, compared with muriate of potash. An increase in yield was observed, with maximum applications equivalent to 80 kg K ha⁻¹, but this was statistically insignificant. Sanz-Scovino and Rowell (1988) comment that application of potassium feldspar may be beneficial as an alternative to KCl in Colombia, where economic and agricultural conditions, including the occurrence of oxisol soils, give rise to disadvantages with the use of KCl.

7.4. Trials with non-granitic bulk rocks

Bulk rocks other than granites and rocks rich in alkali feldspars have been used as a source of soil nutrients in a number of studies, dominated by the use of phosphate rock which is well-established commercially (van Straaten, 2007). In general, trials with silicate rocks, especially volcanic rocks, have not focused on their possible value as a source of K, but as a source of a range of major and trace mineral nutrients.

Leonardos et al. (1987) approach the problem of nutrient supply in laterite systems, where soils (oxisols) are predominantly extremely depleted in nutrients, and have little or no capacity (by virtue of their mineralogy being dominated by quartz, kaolinite and aluminium oxy-hydroxides) to retain nutrients supplied by soluble fertilisers. Leonardos et al. (1987) strongly criticise conventional fertiliser practice that is driven by the industrial world: “Unfortunately, the standard concept and technology of soil fertilizer... is behind that of the superphosphate concept developed by J.B. Lawes in England, 150 years ago. ... Had this technology been originally developed for the deep leached laterite soils of the tropics instead for (*sic*) the glacial and rock-debris-rich soils of the northern hemisphere our present fertilizers might have been quite different.”

Preliminary data for trials with beans (*Phaseolus vulgaris*), napier grass (elephant grass; *Pennisetum purpureum*), and *Eucalyptus pellita* were carried out near Brasilia, using a range of different rock types (Leonardos et al., 1987). For beans, the greatest yields were observed in experiments with basalt applied at the equivalent of 6 T ha⁻¹ and mica schist (as a source of K) applied at the equivalent of 60 kg K ha⁻¹, with N

and P applied as ammonium nitrate and triple superphosphate. For napier grass, yields increased with the application of limestone, basalt and the metamorphic rocks mica schist (mica-rich) and migmatite (feldspar-rich), up to 30% greater than for a control. Eucalyptus’ response was measured by comparing plant height and trunk diameter; both were greatest with application of basalt.

More recently, other experiments have been carried out using volcanic rock (ultramafic rocks from the Mata da Corda; Theodoro and Leonardos, 2006; 30–36% SiO₂). This rock forms bedrock in an area of forest known for its fertility compared with neighbouring soils. Application at the rate of 2.5–3 T ha⁻¹ was recommended to farmers who conducted the trials, which were designed to raise awareness in local people of possible benefits of indigenous rock sources. Soil fertility improved, with measurable increases in Ca, Mg, P and K, and reduction in exchangeable Al. Results were presented based on records of application and yield supplied by participating farmers, including their observations of plant growth. Maize (*Zea mays*), sugar cane (*Saccharum officinarum*), rice (*Oryza sativa*), manioc (*Manihot esculenta*) and corn (*Zea mays*) were used in the trials.

Theodoro and Leonardos (2006) found in every case that application of the rock fertiliser compared to conventional practice with chemical fertilisers gave increased crop yields, most notably for sugar cane. However, in some cases manure was used in combination with the rock dust, and so it is difficult to attribute the observed benefits to rock dust alone. Theodoro and Leonardos (2006) report that the reaction of farmers engaged in the project was very positive to rock dust, and that the project gave many valuable social benefits in addition to the perceived agronomic benefits. The use of rock dust in tropical soils is developed further (without evidence from trials) by Fyfe et al. (2006), on the basis of a range of societal benefits.

Other work has been carried out to determine the behaviour under soil conditions of basaltic rocks (45% SiO₂; Hinsinger et al., 2001; Gillman et al., 2002) and andesitic rocks (typically 58% SiO₂; Meheruna and Akagi, 2006).

In laboratory studies designed to understand weathering phenomena, Hinsinger et al. (2001) assessed the influence of plant growth on the weathering of basalt, and report the results of experiments to assess the extent to which crop plants enhance the release of cations from the rock. In these experiments, lupin (*Lupinus albus* cv Lublanc), oilseed rape (*Brassica napus* cv Drakkar), banana (*Musa paradisiaca* cv Cavendish CV901) and maize (*Zea mays* cv Mona) were compared. The plants were grown in contact with a mesh bag that contained the powdered basalt (0.1–0.2 mm, irrigated with a nutrient solution. The effluent solution was analysed for elements liberated from the basalt that were lacking in the irrigation solution (especially Fe, Ca, Mg, Na, Si). Plant uptake of these elements was monitored with time, so the rate of basalt weathering could be compared between species. Rates of release to the leaching solution were greatest for Mg and Na with lupins, and for Fe with maize. Mass balance calculations showed that maize had greatest uptake of Na, Fe and Si, and banana had greatest uptake of Mg, Fe and Ca. The calculated

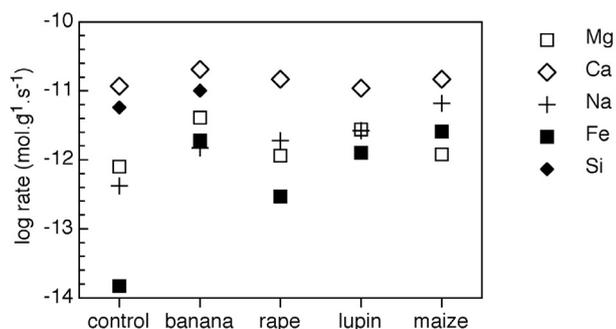


Figure 6. Comparison of dissolution rates for basalt in the presence of different crops (data from Hinsinger et al., 2001).

weathering rates for the basalt are compared in Figure 6. Bearing in mind that the reaction rate is expressed as a logarithm, Figure 6 shows that weathering rate varies from one plant species to another, and differs for different elements. With the exception of Ca, all weathering rates increase in the presence of plant growth, by an order of magnitude for Fe, and by a factor of up to 5 for Mg and Na, for banana, lupin and maize.

Other laboratory experiments are reported by Gillman et al. (2002), who compared the effect of addition of basalt dust on the soil properties for a range of Queensland soil types in experiments involving incubation for 3 months at field moisture capacity. Soil properties (pH, CEC, exchangeable cations, P sorption capacity, extractable P and extractable Si) were determined before and after leaching with the equivalent of 2750 mm rainfall. Exchangeable H and Al were reduced, with an increase in exchangeable Ca and Mg. Basalt released both Si and P to the soil, and gave increased extractable P.

Meheruna and Akagi (2006) carried out experiments similar to those of Hinsinger et al. (2001), using andesite instead of basalt, and growing rice (*Oryza sativa*), maize (*Zea mays*) and soybean (*Glycine max* L.) under hydroponic conditions. Weathering was determined from the release of Si, Ca, Mg, Mn, Fe and Al, which was enhanced in all cases, most notably for Ca and Mg with maize. Weathering rate data were not given, and so cannot be compared directly with results presented by Hinsinger et al. (2001).

Although crushed rock materials have been promoted as nutrient sources for some time, this has been largely through the alternative or organic farming sectors (e.g. Lisle, 1994; Walters, 1975). The use of rock dusts underpins the “Remineralize the Earth” movement (<http://www.remineralize.org>), but as yet there are no published, statistically sound, trials that clearly demonstrate the agronomic value of rock dusts in isolation from other applications to the land, such as manures or composts. The use of rock powders in farming is, however, sufficiently acceptable and widespread to sustain commercial activity, especially with the growth in popularity of organic food.

8. CONCLUSION

Investigations of the possible use of silicate rocks as sources of K have yielded varying results. In general, there is a lack

of consistency in terms of the design of individual trials, limiting comparison and extrapolation. Soil type and properties are rarely reported. Given its inherent inconsistency, the work reported here is limited in the extent to which it can be interpreted. However, it is undeniable that the price of potash has risen considerably since much of the experimental work was carried out, justifying further research.

Laboratory studies of the dissolution of feldspars and nepheline, with or without the presence of mycorrhizal soil microbial communities, have shown that in principle these minerals are capable of releasing K on a timescale that is appropriate to meet the needs of growing plants. When trials have been carried out, results have been variable, and have not always been substantiated by statistically rigorous experimental design or analysis. Nevertheless, the most positive results have been obtained for soils with a very low cation exchange capacity, typical of those of oxisols encountered in tropical/subtropical regions and that have poor nutrient retention characteristics. Thus the application of crushed rock materials, that might be derived from local sources, has to be considered seriously as an alternative to conventional chemical fertilisers where those might be poorly accessible on the grounds of cost or availability.

The price of conventional sources of K is much greater now than at the time of the trials reported here. Thus those reports that dismissed the use of crushed rock materials, especially granite, on economic grounds need to be reconsidered. In circumstances commonly encountered in developing countries, where the price of potash fertilisers on the world market is prohibitively high (especially following recent price rises), it is beneficial to explore the use of locally-sourced igneous rocks as a source of K.

There is clearly scope for careful selection of the silicate rock potassium source. On the basis of dissolution rate data, priority should be given to rocks that contain nepheline. These include nepheline syenites, phonolites and trachytes, rock types that are characteristic of rift valley tectonic settings, and so are available in many countries that might have difficulty funding adequate conventional fertiliser purchases. In geological descriptions, there is some overlap between trachyte and basalt, and areas mapped as basalt may include trachytic rock types. Thus the behaviour of basaltic rocks in crop production systems is relevant in consideration of sources of K, although such rocks generally have relatively low K contents.

If nepheline-bearing rocks are not available, it is appropriate to consider the use of potassium feldspars, one of the commonest minerals in the Earth’s crust. Potassium feldspar often occurs in coarse grained pegmatites, from which it can easily be separated by eye, as well as in granites. Published trials in African and Columbian production systems demonstrate the benefit of application of feldspar for a range of crop types, as a material almost equivalent in performance to soluble potassium fertilisers.

For northern hemisphere countries in which agricultural soils are developed on tills or mechanically weathered rock substrates, or are rich in clay minerals, the ability to retain mineral nutrients is much greater than in tropical regions. In these

circumstances, the use of crushed rocks as a source of K is less likely to be beneficial in general terms, although the long-term replenishment of K from crushed rock sources may be desirable in specific farming practices, such as organic farming.

One of the major problems associated with the use of crushed rocks as a source of K (or other nutrients) is the lack of robust experimental trials that are consistent in terms of both their agronomic and their mineralogical design. It is essential that the two disciplines of biology and mineralogy have equal weight in experiments of this type, as expertise in both is needed. Such trials require substantial investment in terms of time, and so need to be considered strategically. The current high cost of conventional potassium fertilisers coupled with increased demand for crop production both justify strategic investment of this type.

REFERENCES

- Abdel-Mouty M.M., El-Greadly N.H.M. (2008) The productivity of two okra cultivars as affected by gibberilic acid, organic N, rock phosphate and feldspar applications, *J. Appl. Sci. Res.* 4, 627–636.
- Ali H.A., Taalab A.S. (2008) Effect of natural and/or chemical potassium fertilizers on growth, bulbs yield and some physical and chemical constituents of onion (*Allium cepa*, L.), *Res. J. Agric. Biol. Sci.* 4, 228–237.
- Badr M.A. (2006) Efficiency of K-feldspar combined with organic materials and silicate-dissolving bacteria on tomato yield, *J. Appl. Sci. Res.* 2, 1191–1198.
- Bakken A.K., Gautneb H., Myhr K. (1997) The potential of crushed rocks and mine tailings as slow-releasing K fertilizers assessed by intensive cropping with Italian ryegrass in different soil types, *Nutr. Cycl. Agroecosys.* 47, 41–48.
- Bakken A.K., Gautneb H., Sveistrup T., Myhr K. (2000) Crushed rocks and mine tailings applied as K fertilizers on grassland, *Nutr. Cycl. Agroecosys.* 56, 53–57.
- Barlow S.G. (1996) The mineralogical, geochemical and experimental evaluation of boulder clay from Adswold, Stockport, as a model brickclay raw material, PhD thesis (unpublished), University of Manchester, 313 p.
- Barral Silva M.T.B., Hermo B.S., Garcia-Rodeja E., Freire N.V. (2005) Reutilization of granite powder as an amendment and fertilizer for acid soils, *Chemosphere* 61, 993–1002.
- Blum A.E., Stillings L.L. (1995) Feldspar dissolution kinetics, Chemical weathering rates of silicate minerals, in: White A.F., Brantley S.L. (Eds.), *Rev. Mineral.* 31, 291–351.
- Blum W.E.H., Herbinger B., Mentler A., Ottner F., Pollak M., Unger E., Wenzel W.W. (1989) The use of rock powders in agriculture. I. Chemical and mineralogical composition and suitability of rock powders for fertilization, *Z. Pflanzenernah. Bodenk.* 152, 421–425.
- Bolland M.D.A., Baker M.J. (2000) Powdered granite is not an effective fertilizer for clover and wheat in sandy soils from Western Australia, *Nutr. Cycl. Agroecosys.* 56, 59–68.
- Brantley S.L., Stillings L. (1996) Feldspar dissolution at 25 °C and low pH, *Am. J. Sci.* 296, 101–127.
- Coreonos C., Hinsinger P., Gilkes R.J. (1996) Granite powder as a source of potassium for plants: a glasshouse bioassay comparing two pasture species, *Fertil. Res.* 45, 143–152.
- Curtis C.D. (1976) Stability of minerals in surface weathering reactions: a general thermochemical approach, *Earth Sci. Process.* 1, 63–70.
- De Ruiter P.A.C. (1979) The Gabon and Congo basins salt deposits, *Econ. Geol.* 74, 419–431.
- Deer W.A., Howie R.A., Zussman J. (1992) *An Introduction to the Rock Forming Minerals*, 2nd ed., Longman, Harlow, 696 p.
- El Tabakh M., Utha-Aroon C., Schreiber B.C. (1999) Sedimentology of the Cretaceous Maha Sarakham evaporates in the Khorat Plateau of northeastern Thailand, *Sediment. Geol.* 123, 31–62.
- FAO (2008) *Current world fertilizer trends and outlook to 2011–12*, Food and Agriculture Organization of the United Nations, Rome, 44 p.
- Fyfe W.S., Leonardos O.H., Theodoro S.H. (2006) Sustainable farming with native rocks: the transition without revolution, *Anais da Academia Brasileira de Ciencias* 78, 715–720.
- Gillman G.P., Burkett D.C., Coventry R.J. (2002) Amending highly weathered soils with finely ground basalt rock, *Appl. Geochem.* 17, 987–1001.
- Gleeson D.B., Clipson N., Melville K., Gadd G.M., McDermott F.P. (2005) Characterization of fungal community structure on a weathered pegmatitic granite, *Microb. Ecol.* 50, 360–368.
- Goldich S.S. (1938) A study in rock weathering, *J. Geol.* 46, 17–58.
- Goldschmidt V.M. (1933) *Grundlagen der quantitativen Geochemie*, Fortschr. Mineral. Krist. Petrog. 17, 112.
- Harley A.D., Gilkes R.J. (2000) Factors influencing the release of plant nutrients from silicate rock powders: a geochemical overview, *Nutr. Cycl. Agroecosys.* 56, 11–36.
- Hinsinger P., Barros O.N.F., Beneditti M.F., Noack Y., Callot G. (2001) Plant-induced weathering of a basaltic rock: experimental evidence, *Geochim. Cosmochim. Acta* 65, 137–152.
- Hinsinger P., Bolland M.D.A., Gilkes R.J. (1996) Silicate rock powder: effect on selected chemical properties of a range of soils from Western Australia and on plant growth assessed in a glasshouse experiment, *Fertil. Res.* 45, 69–79.
- Lægriid M., Bøckman O.C., Kaarstad O. (1999) *Agriculture, Fertilizers and the Environment*, CABI Publishing, Wallingford, 294 p.
- Le Maitre R.W. (1976) The chemical variability of some common igneous rocks, *J. Petrol.* 17, 589–637.
- Lee M.R., Parsons I. (1995) Microtextural controls of weathering of perthitic alkali feldspars, *Geochim. Cosmochim. Acta* 59, 4465–4488.
- Leonardos O.H., Fyfe W.S., Kronberg B.I. (1987) The use of ground rocks in laterite systems – an improvement to the use of conventional soluble fertilizers, *Chem. Geol.* 60, 361–370.
- Lian B., Wang B., Pan M., Liu C., Teng H.H. (2008) Microbial release of potassium from K-bearing minerals by thermophilic fungus *Aspergillus fumigatus*, *Geochim. Cosmochim. Acta* 72, 87–98.
- Limão N. and Venables A.J. (2001) Infrastructure, geographical disadvantage, transport costs, and trade, *The World Bank Economic Review* 15, 451–479.
- Lisle H. (1994) *The Enlivened Rock Powders*. Acres USA, PO Box 8800, Metairie, Louisiana 70011, ISBN 0-911311-48-3, 194 p.
- Lloyd S.L. (1918) *Mining and manufacture of fertilizing materials and their relation to soils*, Van Nostrand, New York, 125 p.
- Longo R. and Sekkat K. (2004) Economic obstacles to expanding intra-African trade, *World Development* 32, 1309–1321.
- Manning D.A.C. (1995) *Introduction to Industrial Minerals*, Chapman and Hall, London, 276 p.
- Martin J.M., Meybeck M. (1979) Elemental mass-balance of material carried by major world rivers, *Marine Chemistry* 7, 173.

- Meheruna A. Akagi T. (2006) Role of fine roots in the plant-induced weathering of andesite for several plant species, *Geochem. J.* 40, 57–67.
- Mengel K., Rahmatullah (1994) Exploitation of potassium by various crop species from primary minerals in soils rich in micas, *Biol. Fert. of Soils* 17, 75–79.
- Mengel K., Rahmatullah, Doh H. (1998) Release of potassium from the sily and sand fraction of loess-derived soils, *Soil Sci.* 163, 805–813.
- Moore S. (2009a) Fertiliser loses its mineral appetite, *Ind. Minerals*, 36–41.
- Moore S. (2009b) Potash tunnel vision, *Ind. Minerals*, 56–62.
- Ober J.A. (2007) Potash, 2006 Minerals Yearbook, United States Geological Survey, Reston, VA.
- Riggs K.S., Syers J.K., Appleton J.D. (1993) Dissolution of potassium feldspar rocks in soils in open leaching and closed-incubation systems, *J. Sci. Food Agr.* 62, 409–412.
- Rittenhouse P.A. (1979) Potash and politics, *Econ. Geol.* 74, 353–357.
- Rosling A., Lindahl B.D., Taylor A.F.S., Finlay R.D. (2004) Mycelial growth and substrate acidification of ectomycorrhizal fungi in response to different minerals, *FEMS Microbiol. Ecol.* 47, 31–37.
- Rudnick R.L., Gao S. (2003) The Composition of the Continental Crust, pp. 1–64, in: Rudnick R.L. (Ed.), *The Crust*, Vol. 3, Treatise on Geochemistry, Holland H.D., Turekian K.K. (Eds.), Elsevier-Perгамon, Oxford.
- Sanz Scovino J.I., Rowell D.L. (1988) The use of feldspars as potassium fertilizers in the savannah of Columbia, *Fertil. Res.* 17, 71–83.
- Searls J.P. (2000) Mineral Industry Surveys, Potash, 1999 Annual Review, United States Geological Survey, Reston, VA.
- Sheldrick W.F., Lingard J. (2004) The use of nutrient audits to determine nutrient balances in Africa, *Food Policy* 29, 61–98.
- Sheldrick W.F., Syers J.K., Lingard J. (2002) A conceptual model for conducting nutrient audits at national, regional and global scales, *Nutr. Cycl. Agroecosys.* 62, 61–67.
- Sheldrick W.F., Syers J.K., Lingard J. (2003) Soil nutrient audits for China to estimate nutrient balances and output/input relationships, *Agr. Ecosyst. Environ.* 94, 341–354.
- Sposito G. (1989) *The Chemistry of Soils*, Oxford University Press, Oxford, 277 p.
- Sutherland D.S. (1967) A Note on the Occurrence of Potassium-Rich Trachytes in the Kaiserstuhl Carbonatite Complex, West Germany, *Mineral. Mag.* 36, 334–341.
- Theodoro S.H., Leonardos O.H. (2006) The use of rocks to improve family agriculture in Brazil, *Anais da Academia Brasileira de Ciencias* 78, 721–730.
- Tole M.P., Lasaga A.C., Pantano C., White W.B. (1986) The kinetics of dissolution of nepheline (NaAlSi₃O₈), *Geochim. Cosmochim. Acta* 50, 379–392.
- van Straaten P. (2006) Farming with rocks and minerals: challenges and opportunities, *Anais da Academia Brasileira de Ciencias* 78, 731–747.
- van Straaten P. (2007) *Agrogeology: the use of rocks for crops*, Enviroquest Ltd., Cambridge, Ontario, 440 p.
- von Wilpert K., Lukes M. (2003) Ecochemical effects of phonolite rock powder, dolomite and potassium sulfate in a spruce stand on an acidified glacial loam, *Nutr. Cycl. Agroecosys.* 65, 115–127.
- Wallander H., Wickman T. (1999) Biotite and microcline as potassium sources in ectomycorrhizal and non-mycorrhizal *Pinus sylvestris* seedlings, *Mycorrhiza* 9, 25–32.
- Walters C. (editor) (1975) *The Albrecht Papers, Volume 1 – Foundation concepts*, Acres USA, PO Box 8800, Metairie, Louisiana 70011, ISBN 0-911311-05-X, 515 p.
- Wang J.G., Zhang F.S., Cao Y.P., Zhang X.L. (2000) Effect of plant types on release of mineral potassium from gneiss, *Nutr. Cycl. Agroecosys.* 56, 37–44.
- Weerasuriya T.J., Pushpakumara S., Cooray P.I. (1993) Acidulated pegmatitic mica – a promising new multi-nutrient mineral fertilizer, *Fertil. Res.* 34, 67–77.
- White A.F. (1995) Chemical weathering rates of silicate minerals in soils, Chemical weathering rates of silicate minerals, in: White A.F., Brantley S.L. (Eds.), *Rev. Mineral.* 31, 407–461.
- Woolley A.R. (2001) *Alkaline rocks and carbonatites of the world. Part 3: Africa*, Geological Society of London, London, 372 p.