Chapter 2

Inputs: Potassium Sources for Agricultural Systems

Robert L. Mikkelsen and Terry L. Roberts

Abstract In the potassium (K) cycle, inputs encompass all K sources that move into a given volume of soil. These inputs may include atmospheric deposition, irrigation water, runoff, erosion, as well as seeds, cuttings, and transplants. Accounting for all inputs is seldom routinely done on the farm. Many K inputs have variable concentrations, making estimations difficult. Estimates for added K are provided in some planning documents and can be used where testing of on-farm inputs is not feasible, although testing is preferred. Standard commercial fertilizers have known concentrations of K and are concentrated enough to be economical to transport long distances. The global reserves for their production have an estimated lifetime of thousands of years. This chapter emphasizes considerations for using various commercial fertilizer sources.

2.1 Overview of Potassium Inputs

Potassium (K) inputs as a group is *the total quantity of K, originating outside a given volume of soil, that moves into that volume* (Fig. 2.1). Inputs include K in atmospheric deposition; irrigation water; K transported to the soil volume via runoff and erosion from other areas; K in seeds, cuttings, transplants, or residues; organic fertilizer applications; and commercial fertilizer additions. This pool is the sum of all these inputs. Inputs may occur directly to the soil or, as is the case with foliar fertilizer applications, directly to the plant.

For making improvements in K recommendations, this chapter emphasizes inorganic and organic fertilizer inputs. Of all the inputs, these are the ones that farmers have the greatest control over. This chapter defines organic inputs as K sources

R. L. Mikkelsen (✉)

African Plant Nutrition Institute and University Mohammed VI Polytechnic, Ben Guerir, Morocco

e-mail: r.mikkelsen@apni.net

T. L. Roberts

Formerly International Plant Nutrition Institute (IPNI), Peachtree Corners, GA, USA

Fig. 2.1 The K cycle involves inputs, outputs, and transformations that occur in agricultural soils. Potassium biogeochemistry includes complex chemical, physical, geological, and biological processes within natural or managed ecosystems. This level of complexity has too often been overlooked for K. This figure outlines the major K pools and fluxes occurring within the rootzone during an annual cropping season. It is not comprehensive of all possible inputs, outputs, and transformations that can occur

derived from animal wastes (manure and biosolids) and plant residues. This definition is used to clarify that these inputs do not refer to K sources approved for the production of agricultural products labeled as “organic.” Although the emphasis in this chapter is primarily on inorganic sources, we briefly mention other inputs.

2.2 Atmospheric Deposition

Atmospheric deposition is the quantity of K transferred from the atmosphere to a given area of land (adapted from National Agricultural Library 2019a). Atmospheric deposition is the sum of wet deposition and dry deposition. **Wet deposition** is the quantity of K transferred from the atmosphere to a given area of land by rain, fog, or snow (adapted from National Agricultural Library 2019b). **Dry deposition** is the

quantity of K in atmospheric particles transferred to a given area of land (adapted from American Meteorological Society 2012). Dry deposition is the K in the deposited particles, while wet deposition is the K dissolved in precipitation. For both sources, K deposited on both soil and foliage are considered.

It is well documented that atmospheric transport takes place at very large scales (e.g., from Africa to South America; Prospero et al. 2014). However only a few studies have mapped K deposition at these large scales. In a study conducted in Northern China across ten sites and 3 years, Pan and Wang (2015) measured both wet and dry deposition of K. The average atmospheric deposition, the sum of wet and dry, ranged from 11 to 25 kg K ha⁻¹ year⁻¹ across sites. At all but two sites, average dry deposition was several times greater than wet deposition, indicating that substantially more K was added in particles than in precipitation. Fluxes varied by time of year. The largest fluxes of dry deposition occurred in the spring, which the authors attributed to long-range transport of dust from deserts and loess deposits by 16 dust storms over the 3-year study period. The largest fluxes of wet deposition occurred in summer, which was the rainy season. Deposition also varied spatially, with the greatest atmospheric deposition in industrial areas and the smallest in agricultural areas.

Deposition of K across the contiguous 48 states of the United States was evaluated by Mikhailova et al. (2019) based on data from the US Atmospheric Deposition Program. Total inputs, the sum of both wet and dry deposition, ranged from 0 to 2.5 kg ha⁻¹ year⁻¹ and varied markedly across states.

In power plants, the K composition of particulates in ash depends on the source of fuel. Ruscio et al. (2016) compared three sources of biomass fuel (olive residue, maize residue, and torrefied pine sawdust) to three sources of coal (bituminous, sub-bituminous, and lignite). In both coarse (560–1000 nm) and fine (100–180 nm) submicron particles of ash, the K concentrations in maize and olive waste were over 30%, several times higher than in any other fuel source. Ashes from coal sources were all less than 7% K across both particle size ranges. In the future, power plants relying solely on biomass feedstocks or power plants that cofire coal and biomass will have greater quantities of K in ash than traditional coal-only power plants. The high K content of ash from crop residues (e.g., 6% K in rice (*Oryza sativa* L.) straw ash; Hung et al. 2020) suggests that in areas where residues are burned in fields as a management practice, some K will be lost from fields and redeposited elsewhere in the environment, including nearby fields.

2.3 Irrigation Water

The quantity of K input by irrigation water is determined by the K concentration in the water source, the quantity of water used, the quantity of sediment transported with the water, and the K content in the sediment. For example, Hoa et al. (2006) examined K inputs into flooded rice fields in the Mekong Delta of Vietnam and found, on average, K input by irrigation water was 14–18 kg K ha⁻¹ year⁻¹.

They also found that large amounts of K were added by the sediment in the water. The total quantity of K added ranged from 320 to 1892 kg K ha⁻¹ year⁻¹, but only 3–10 kg ha⁻¹ year⁻¹ was plant available, based on commonly used interpretations of the soil test used in the study. Over time, a portion of the remaining K in the sediment was expected to become available for plant uptake, based on transformations in the soil and the mechanisms used by plants to access K in various soil pools. The considerations of this study extend more generally to K input by runoff and erosion.

The waterborne K input can be rather large in some irrigated fields. For example, a common water source used for irrigating cotton (*Gossypium hirsutum* L.) in California contains ~0.3 mmol K L⁻¹. During the growing season, adding 7.5 ML ha⁻¹ of irrigation water supplies approximately 90 kg K ha⁻¹ year⁻¹ to the soil.

2.4 Runoff and Erosion

The loss of K with soil materials leaving agricultural fields is covered extensively in Chap. 3. Soil materials are most commonly transported by wind, by flowing water, and through slow hillside creep. These transport processes are complex and are the subject of detailed investigations (Williams 2012). However, these erosional materials are subsequently deposited again in another part of the landscape.

Particle deposition may be transitory, or it may persist for geologic periods (such as chalk and apatite). The eroded materials are deposited off-site from their source, too often resulting in clogged drainage ways, silted reservoirs, and a destruction of aquatic habitat. The loss of eroded soil directly leads to soil degradation through nutrient depletion and removal of valuable soil organic matter.

How much of the eroded material is carried back to the sea or is stored in river terraces, flood plans, or reservoirs is site specific. Sediments stored in reservoirs show an accumulation in nitrogen (N), phosphorus (P), and K that corresponds to watershed fertilizer application rates (Junakova and Balintova 2012).

The distribution of nutrients in reservoir sediments is not uniform, as the K-rich materials associated with the fine particles tend to settle more slowly than the larger-sized eroded material. Sediments can supply significant amounts of bioavailable K when it is dredged and added back to agricultural land (e.g., Woodard 1999; Darmody and Ruiz 2017).

2.5 Seeds, Cuttings, Transplants, and Residues

Very small amounts of K are added to the field during planting operations. Seeds and seedlings contain K in quantities that are commonly overlooked while calculating nutrient budgets. The mineral content of agronomic seeds will vary somewhat [e.g., maize seed can contain ~3 mg K g⁻¹, while tomato seeds contain 5 mg K g⁻¹ (Liptay

and Arevalo 2000)]. As an example, a typical maize field planted with 60,000 seeds ha^{-1} will add approximately 25 g K in the process. This seed-borne K provides nutrition during the germination process and the initial growth of the embryo. Once the seedling begins growing, the K demand from the soil quickly increases.

When seedlings are used for transplanting, a small amount of K is brought to the field. Using tomatoes as an example, transplanting 2000–3000 plants ha^{-1} will add between 600 and 900 g K to the field (Liptay and Arevalo 2000). When vineyards and orchards are established, small amounts of K will also be moved to the site in the woody tissue of the planting material.

Crop residues that remain in the field do not contribute to the K balance of the field, but when residues are imported from other fields or farms, they can contribute significant amounts of additional K. These residue inputs are discussed later.

2.6 Organic Fertilizer

The use of approved nutrient sources for organic crop production is governed by a variety of oversight organizations. Unfortunately, each of these organizations maintains somewhat different standards and allows different materials to be used in their organic production systems because they individually interpret the intent of organic agricultural principles. As a result, a grower seeking advice on permissible K materials should first know where the agricultural produce will be sold in order to meet the requirements of that market.

In general, regulations for mined K sources specify that they must not be processed, purified, or altered from their original form. However, there is disagreement among different certifying bodies over what specific materials can be used. Unfortunately, some of these restrictions on certain nutrient materials do not have solid scientific justification, and their inclusion or exclusion on various lists should not be viewed as one material being more or less “safe” than another fertilizer material (Mikkelsen 2007). Certain wastes (e.g., ash materials) and unprocessed minerals (e.g., glauconite) may also be permitted for organic crop production in certain conditions.

In the mixed livestock/crop systems, the nutrition of the animals generally takes first priority, and the residual manure is returned to surrounding cropland. In these cases, K imported to the farm in feed and bedding frequently exceeds the output in milk and meat products, sometimes leading to an accumulation of K in the surrounding fields that receive manure. Large losses of K often occur on these farms during manure storage and composting. Because excreted K is mostly expelled as urine, if this fraction is not effectively recovered in confined animal operations, most of the K will not be returned to the field with the solid portion of the manure.

The nutrient value of K in animal manures is generally equivalent to soluble K fertilizers. Since K is not a structural component of plant or animal cells and remains soluble in animal manure and urine, there is no true “organic” K.

Table 2.1 Approximate dry matter and K₂O content of selected animal manures. (IPNI 2012)

		Dry matter	K ₂ O content
Livestock type	Waste handling system	%	kg t ⁻¹
<i>Solid handling systems</i>			
Swine	Without bedding	18	4
	With bedding	18	3.5
Beef cattle	Without bedding	15	5
	With bedding	50	13
Dairy cattle	Without bedding	18	5
	With bedding	21	5
Poultry	Without litter	45	5
	With litter	75	17
	Deep pit (compost)	76	22.5
<i>Liquid handling systems</i>			
Swine	Liquid pit	4	9.5
	Oxidation ditch	2.5	9.5
	Lagoon	1	0.2
Beef cattle	Liquid pit	11	17
	Oxidation ditch	3	14.5
Dairy cattle	Lagoon	1	2.5
	Liquid pit	8	14.5
Poultry	Lagoon	1	2.5
	Liquid pit	13	48

The chemical composition of manures should be determined through laboratory analysis in order to apply material at rates that avoid either excessive or insufficient application of K to the field. Solid manures frequently contain between 5 and 25 kg K₂O Mg⁻¹, while liquid pit manures typically contain 1–4 kg K₂O 1000 L⁻¹ (Table 2.1). Lagoon liquids have an even lower K concentration. When repeated applications of animal manures are used as a primary source of N for plant nutrition (such as on organic farms), the accumulation of excessive concentrations of K and P in the soil is common (Mikkelsen 2000a; Arienzo et al. 2009). Potassium concentration can change from load to load and also throughout the year (O'Dell et al. 1995). Agitation of manure pits prior to loading can reduce variability because it creates a more uniform distribution of manure solids (Duo et al. 2001).

In addition to recoverable manure, there can be significant amounts of K returned directly to the soil via animal urination and defecation. For example, at the localized site of grazing dairy cattle urination, effective application rates can reach 1000 kg K ha⁻¹ in this small patch (Williams et al. 1990).

Nutrient concentrations in manure are generally low enough that it is uneconomical to transport manure long distances. Therefore, manure use is primarily local, often restricted to a single farm or nearby farms. There are also many cases where manure has not been distributed across an entire farm but instead spread only on fields nearest where animals were kept (Mikkelsen 2000b). Often overlooked, animal manure has additional benefits beyond just its mineral nutrient content and can aid in building and remediating soil (Mikha et al. 2017).

Fig. 2.2 Average wheat and corn yields for a 15-year study in Hunan, China, receiving combinations of N, P, K, and farmyard manure. (adapted from Zhang et al. 2009)

Evidence from long-term experiments show that combinations of inorganic and organic nutrients often achieve higher crop yields, improve soil quality and fertility, increase nutrient use efficiency, and lead to more sustainable nutrient management systems than either source alone (Miao et al. 2011). For example, Zhang et al. (2009) reported on a 15-year maize (*Zea mays* L.)—wheat (*Triticum aestivum* L.) rotational study in China where significant yield responses to N occurred for the first few years, but adding both N and P together increased yields fivefold, although yields decreased subsequently. Applying K along with N and P further increased yields in some years, but high yields were only sustained when farmyard manure was added with the N, P, and K (Fig. 2.2). The addition of farmyard manure prevented yields from declining over time and helped maintain the fertility and buffering capacity of the soil.

2.7 Commercial Fertilizer

Commercial fertilizer is the K input farmers can manage with the greatest accuracy and precision. In countries where the compositions of fertilizers are regulated, minimum concentrations of K are guaranteed by the fertilizer manufacturer and do not vary from the stated label. Inaccuracies in applying the correct amount arise from problems with distributing the products properly over the field, rather than from the composition of the products themselves. However, fertilizer composition integrity is not always assured in some parts of the world, and adulterated products find their way to the marketplace. Modern K fertilizers are manufactured with sufficiently high

nutrient concentrations that they are economical to transport long distances, allowing them to be affordably shipped anywhere in the world where logistics permit.

Of all the sources enumerated above, regulated commercial fertilizers are the only inputs farmers do not need to test to know the K concentrations. The need to test other inputs prior to application means that an accurate accounting of all K inputs is rarely performed routinely on the farm. Where testing is feasible and economical, many farmers do test manure and irrigation water, especially if incentives or regulations are in place. Where testing is not practical, published estimates are used, but their inaccuracies for local conditions must be acknowledged.

2.7.1 Resources and Reserves

Potassium minerals and salts mined for use as fertilizers are generally referred to as potash, a term dating back to the nineteenth century when K used for fertilizer came from “potashes.” Potash is a general term encompassing many different individual K fertilizers. Among these sources are potassium chloride (KCl), also called muriate of potash (MOP); potassium sulfate (K_2SO_4), also called sulfate of potash (SOP); potassium magnesium sulfate ($K_2SO_4 \cdot MgSO_4$), sometimes referred to as sulfate of potash magnesia (MgSOP or SOPM); potassium nitrate (KNO_3), also called nitrate of potash (NOP) or saltpeter; and mixed sodium-potassium nitrate ($NaNO_3 + KNO_3$), also called Chilean saltpeter. The K concentration of commercial fertilizers is reported either on an oxide basis (K_2O) or on an elemental basis (K). For a given concentration of elemental K, the reported oxide concentration is 1.2 times that of the reported elemental concentration: $K_2O = 1.2 \times K$.

Potassium is the seventh most abundant element in the Earth’s crust (Fountain and Christensen 1989) but is never found in its elemental form in nature because it is highly reactive unless chemically bound to other elements. Feldspars, micas, and other silicate minerals contain significant amounts of K, but they are not currently commercial sources of potash.

Global potash resources most commonly occur as large, deeply buried deposits associated with marine evaporite sequences and, less commonly, with non-marine evaporites generally formed in arid climates (Sheldrick 1985; IFDC and UNIDO 1998). Sylvite, the mineral form of potassium chloride, is the most abundant mineral in commercial deposits (Table 2.2). Sylvinite, a physical mixture of sylvite and halite (NaCl), is the most common K-bearing ore. The second most common ore is carnallite, a mixture of primarily carnallite ($KCl \cdot MgCl_2 \cdot 6H_2O$) and other salts. Other less common ores include kainite ($KCl \cdot MgSO_4 \cdot 3H_2O$), langbeinite ($K_2SO_4 \cdot 2MgSO_4$), polyhalite ($K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$), and hartsalz, a physical mixture of sylvite, halite, kieserite, and/or anhydrite. Potassium nitrate (niter) is a unique ore, with deposits occurring only in the Atacama Desert of northern Chile.

The world has abundant potash resources. There are approximately 980 deposits on five continents (Orris et al. 2014). The US Bureau of Mines and the US Geological Survey (1980) define a **resource** as *a concentration of naturally*

Table 2.2 Names, chemical formulas, and K concentrations of some common K-bearing minerals used in production of potash fertilizers

Mineral	Chemical name	Chemical formula	Weight % K ₂ O
Carnallite	Potassium magnesium chloride	KCl·MgCl ₂ ·6H ₂ O	17
Carnallitite (ore)	Mixture of carnallite, halite, and others	KCl·MgCl ₂ ·6H ₂ O, NaCl, MgSO ₄ ·H ₂ O, CaSO ₄	Variable
Hartsalz (ore)	Mixture of sylvite, halite, and kieserite	KCl, NaCl, MgSO ₄ ·H ₂ O, CaSO ₄	Variable
Kainite	Potassium magnesium sulfate chloride	KCl·MgSO ₄ ·3H ₂ O	19
Langbeinitite	Potassium magnesium sulfate	K ₂ SO ₄ ·2MgSO ₄	23
Niter	Potassium nitrate	KNO ₃	46
Polyhalite	Potassium magnesium calcium sulfate	K ₂ SO ₄ ·MgSO ₄ ·2CaSO ₄ ·2H ₂ O	16
Schoenite	Potassium magnesium sulfate	K ₂ SO ₄ ·MgSO ₄ ·6H ₂ O	23
Sylvinitite (ore)	Mixture of sylvite and halite	KCl, NaCl	Variable
Sylvite	Potassium chloride	KCl	63

occurring solid, liquid, or gaseous material in or on the Earth's crust in such a form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible. Feasibility depends on factors such as product prices, capital costs, and current and potential mining and processing technologies. The **reserve base** is that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. A **reserve** is that part of the reserve base which could be economically extracted or produced at the time of determination. The quantity of reserves depends on factors such as expected product prices, capital costs, and current mining and processing technologies. Global potash reserves are estimated to be 250 billion metric tonnes (USGS 2020). That is sufficient potash for thousands of years, even if fertilizer production was to double.

The global K fertilizer industry is relatively mature and stable. However, there are many commercial endeavors underway to further develop geologic K resources around the world. In Africa, for example, the Danakil region of Ethiopia and Eritrea is being developed to be a major K producer. Resources in the Khemisset region of northern Morocco and the Sintoukola region in the west of the Republic of the Congo are under development as K fertilizer sources. Additionally, geologic accumulations of K in Western Australia and the Western United States are being developed as new K sources. The deep mine in North Yorkshire, UK, is also expected to bring new supplies of K to the commercial fertilizer market.

The percent minable K₂O ore reserves and resources vary widely in potash deposits. Mining costs depend on the depth to the ore, thickness, and uniformity of the potash bed, strength, and uniformity of the overlying strata, flooding risks, and other factors. Even so, potash mining and refining is a much simpler process than is

Table 2.3 Estimated global K₂O reserves and 2019 mine production. All values are in thousands of metric tonnes of K₂O (kt K₂O). (USGS 2020)

	Reserves	% of total reserves	Mine production (2019)	% of total production
Country	kt K ₂ O	%	kt K ₂ O	%
Canada	1,000,000	28	13,300	32
Belarus	750,000	21	7000	17
Russia	600,000	17	6800	17
China	350,000	10	5510	13
Germany	150,000	4	3000	7
Israel	Large	(~5)	2000	5
Jordan	Large	(~5)	1500	3
Chile	100,000	3	950	2
Spain	68,000	2	600	1
Brazil	24,000	1	200	1
World total (rounded)	>3,600,000		41,000	

required for the manufacture of nitrogen and phosphorus fertilizers (Rahm 2017). Unlike the Haber-Bosh process for ammonia synthesis or wet process phosphoric acid production, potash processing does not involve complicated chemical reactions; the K is most commonly separated from the other compounds in the ore by flotation and selective crystallization.

Buried potash deposits can range from a few hundred to more than 3000 m deep and are obtained by conventional shaft mining using continuous mining machines that cut into the face of the deposit. Flexible conveyors are attached to the mining machines that convey the ore to the shaft for transport to the surface for processing. Most underground mines utilize room and pillar mining techniques to maintain structural integrity. Solution mining is used for deeper deposits. Hot water is first pumped into the deposit through bore holes to dissolve the ore, and then brine is injected to selectively dissolve KCl, which is withdrawn through another nearby well. Solution mining is energy intensive but is better suited to extremely deep deposits and to some ores such as carnallite. For K-rich surface brines, potash is obtained by solar evaporation in shallow ponds and selective separation of the salts. A floating dredge or other heavy equipment is used to harvest the pond minerals. Underground deposits account for about 75% of global output: 70% from shaft mining operations and 5% from solution mining (Rahm 2017).

Although there are approximately 980 deposits of potash distributed around the world, potash is mined in less than 20 countries (Table 2.3). Russia, Canada, Belarus, and China account for three-quarters of world production. Since 2000, global production has increased at a compound annual growth rate of about 3.1%: from 24.5 Mt. K₂O in 2000 to 41.0 Mt in 2019 (Fig. 2.3). Erratic production has followed volatile prices. Potash prices spiked to record highs in 2008 which decreased demand and production the following year during the global recession and financial crisis.

Fig. 2.3 Global potash mine production between 2000 and 2019. (Jasinski 2020)

2.7.2 Materials and Use

Over 95% of global potash fertilizer production originates with MOP obtained from sylvinite, carnallite, or hartsalz (Fig. 2.4). In 2015, approximately 74% of the KCl produced was used directly for plant nutrition. Of the remaining 26%, about 2% was reacted with nitric acid or nitrate salts to produce NOP, 5% was reacted with sulfuric acid to produce SOP, and 19% was incorporated into various N and P sources to produce N-P-K or P-K complex/compound fertilizers. The next largest quantity of fertilizer produced was primary SOP originating from kainite, hartsalz, or polyhalite, comprising about 4% of 2015 global fertilizer production. The remaining 1% of production was SOPM originating from langbeinite. Polyhalite is expected to become more common as new mines open. About 10% of global K production was used for industrial purposes or as an ingredient in animal feed. The remainder was used for crop nutrition.

The plant K nutritional value is identical for all K sources; however, their properties and solubility vary considerably (Table 2.4). All common commercial K fertilizers are sufficiently soluble to provide adequate K to plants growing in moist soil. Differences in water solubility become important when solid K sources are dissolved for use in foliar sprays or fluid fertilizers. When solid K fertilizers are used for these purposes, both the solubility and the time required for dissolution need to be considered when making a suitable liquid fertilizer. There are additional restrictions to consider when selecting a K source for organic crop production (Mikkelsen 2007).

Fig. 2.4 The process for making final products of common K fertilizers, beginning with the mined ores; quantities are for 2015. (adapted from Rahm 2017)

Table 2.4 Selected properties of common K fertilizers

Fertilizer name	Chemical formula	K content	Solubility
		Weight % K ₂ O	g L ⁻¹ at 20° C
MOP	KCl	60–63	344
SOP	K ₂ SO ₄	50	111
NOP	KNO ₃	45	316
Potassium thiosulfate (KTS)	K ₂ S ₂ O ₃	25	Fluid
Langbeinite (SOPM)	K ₂ SO ₄ ·2MgSO ₄	21	240
Polyhalite	K ₂ SO ₄ ·MgSO ₄ ·2CaSO ₄ ·2H ₂ O	13	12–18 (25 °C)
Potassium hydroxide	KOH	83	1120
Potassium phosphate	KH ₂ PO ₄	34	226
Potassium chloride and kieserite	KCl·MgSO ₄ ·H ₂ O	40	

2.7.2.1 Potassium Chloride (MOP)

Potassium chloride is by far the most widely used K fertilizer for crop nutrition due to its relatively low cost and highest percentage of K_2O , 60–63% (Table 2.4). This high concentration means handling, storage, transport, and application costs are lower for KCl than for other sources. Most KCl fertilizer is produced by separating sylvinite ore into sylvite (KCl) and halite (NaCl), based on either their differing specific gravities or differing solubilities. The resulting purified sylvite-based fertilizer may have a reddish color arising from trace concentrations of iron oxide that are naturally occurring in the ore. Most of the MOP produced is used directly as a fertilizer; however, MOP can also be used to formulate other K fertilizer products (Fig. 2.4).

Potassium chloride is often spread onto the soil surface prior to tillage and planting or applied in a concentrated band near the seed or plant. Since all K fertilizers will increase the soluble salt concentration in the soil as they dissolve, banded KCl is typically placed to the side of the seed to avoid potential osmotic damage during germination. White-colored KCl is sometimes a more purified grade that can be solubilized as a component of fluid fertilizers and foliar sprays or for application through irrigation systems. Potassium chloride, as are most K fertilizers, is available in several particle sizes (from coarse to fine) to match the intended purpose.

2.7.2.2 Potassium Sulfate (SOP)

Potassium sulfate can be produced in three ways. Primary SOP originates from decomposition of ores containing sulfate (Fig. 2.4). As an example, water is added to kainite, producing schoenite as an intermediate product (for the chemical formulas, see Table 2.2). Potassium chloride is then added to the schoenite to produce K_2SO_4 . A second method is to evaporate naturally occurring brines to crystallize K_2SO_4 . Third, the Mannheim process reacts KCl with sulfuric acid, producing K_2SO_4 , as indicated in Fig. 2.4. Potassium sulfate is available in either a crystalline form or as granules that are generally preferred for blending and uniform spreading. The K_2O content is approximately 50% (Table 2.4). In 2015, the primary production of K_2SO_4 accounted for about 9% of global K fertilizers.

Potassium sulfate provides both K and sulfur (S) in forms that are readily soluble and available to plants (SOPIB 2015). There may be certain soils and crops where K is needed but the addition of chloride (Cl^-) should be avoided. In these situations, K_2SO_4 makes a very useful K fertilizer source. Potassium sulfate is only one-third as soluble as KCl, so it is not as commonly used for application through irrigation water unless there is a need for additional S. Foliar sprays of K_2SO_4 are a convenient way to apply additional K and S to plants, supplementing the nutrients taken up from the soil by plant roots. Fine particles are used for making solutions for fertigation or foliar sprays since the small particles dissolve more rapidly. Due to the extra costs

associated with producing K_2SO_4 , the price is generally greater than KCl per unit of K.

Atmospheric deposition of S reduces the need for S fertilization. Most deposition originates from coal and petroleum combustion (Smith et al. 2011). In China, S deposition has been increasing (Smith et al. 2011), and bulk deposition in southeast China has been as high as $71 \text{ kg ha}^{-1} \text{ year}^{-1}$ (Liu et al. (2016)). In contrast, since the Clean Air Act was enacted in the United States, S deposition in that country has been declining (Smith et al. 2011), with areas that historically had the highest quantities of deposition now receiving only $15 \text{ kg S ha}^{-1} \text{ year}^{-1}$ (Zhang et al. 2018). Because these changes occur over decades they can go unnoticed, leading to unknowingly outdated fertilizer recommendations for S. The use of SOP can help alleviate this increasing extent of S deficiency.

2.7.2.3 Potassium Nitrate (NOP)

There are several ways to produce potassium nitrate (Fig. 2.4). In two of them, KCl is mixed with nitrate salts, either sodium nitrate or ammonium nitrate. It is also commonly manufactured by the reaction of KCl with nitric acid. A relatively small amount of KNO_3 is produced from natural caliche deposits from the Chilean desert. Potassium nitrate has a K content of about 45% (Table 2.4).

The agronomic use of KNO_3 is often desirable in conditions where a highly soluble, chloride-free source of both K and N is needed. Potassium nitrate contains a relatively high proportion of K, with a N:K ratio of approximately 1:3 by weight. Applications of KNO_3 are typically made to the soil as prills, dissolved in a solution sprayed on plant foliage, or dissolved and applied through fertigation. Its use is most common for fertilizing high-value specialty crops, including fruits, vegetables, and tobacco (*Nicotiana tabacum* L.).

2.7.2.4 Potassium Thiosulfate (KTS)

Potassium thiosulfate is a clear fluid fertilizer. It is produced by reacting potassium hydroxide with aqueous ammonia, sulfur dioxide, and elemental S. It is used for direct soil application, in irrigation water, or as a foliar fertilizer. The thiosulfate portion of the molecule ($S_2O_3^{2-}$) oxidizes in soil to form sulfate (SO_4^{2-}) during an acid-forming process (Goos and Johnson 2001). The thiosulfate molecule has been shown to delay nitrification (Cai et al. 2018) and to sequester metals, particularly iron (Nayak and Dash 2006).

2.7.2.5 Langbeinite (SOPM)

Langbeinite (Table 2.2) has K, magnesium (Mg), and S all contained within a single geologic mineral. Its composition provides a uniform distribution of these nutrients when applied to the soil. The major source of langbeinite is from deposits in the

Southwest United States. Langbeinite is totally water soluble, but is slower to dissolve than some other common K fertilizers because of the higher particle density (2.8 g cm^{-3} compared with 2 g cm^{-3} for sylvite). This slower dissolution is an advantage in purification, as simple washing removes other impurities, leaving the less-soluble langbeinite (Harley and Atwood 1947). SOPM is frequently used where a low Cl^- source of K is desirable for crop nutrition or where additional Mg may be desired in the farming system, such as on acid soils or on soils where forage is produced for dairies. Langbeinite is a nutrient-rich fertilizer with a relatively low overall salt index. It is available in either a crystalline or granulated form. Langbeinite accounts for less than 1% of global production of primary K fertilizer.

2.7.2.6 Polyhalite

This soluble geologic mineral contains four essential plant nutrients: K, Mg, S, and calcium (Ca) (Table 2.2). The exact chemical formula will vary depending on its geologic origins. Polyhalite is frequently used in situations where a K fertilizer with a low Cl concentration is desirable. The lower K concentration in polyhalite ($\sim 13\% \text{ K}_2\text{O}$) relative to other K fertilizer sources can in cases be compensated by the value of the additional Ca, Mg, and S in each particle (Yermiyahu et al. 2017). The lower solubility may also cause polyhalite to perform as a slightly slow-release source of nutrients, depending on the particle size (Barbier et al. 2017). Commercial supplies of polyhalite come from deep deposits in the Yorkshire region of the United Kingdom and in New Mexico, USA. In practice, both polyhalite and langbeinite are often blended with other less expensive K sources to obtain the desired blend of nutrients.

2.7.2.7 Potassium Hydroxide (KOH)

Potassium hydroxide (KOH) is a strongly alkaline liquid. It is commonly used as a component of fluid fertilizers. It has a low salt index, is free of Cl^- , and contains 83% K_2O (Table 2.4). It is commonly used to neutralize excess acidity in liquid fertilizer blends, irrigation water, and soil. Extreme safety measures must be used when handling this caustic material. Its use as a K source is generally limited to situations where the strongly alkaline properties are desired rather than its inherent K concentration.

2.7.2.8 Potassium Phosphate

Potassium phosphate (KH_2PO_4) is produced from the reaction of KCl with phosphoric acid (Fig. 2.4). It contains 34% K_2O (Table 2.4). This highly soluble product is commonly used in fertigation and for foliar applications where a source of both P and K is desired without additional N.

2.7.2.9 Mineral/Silicate K

Many geologic minerals contain abundant K, but their solubility is generally too low for agronomic use (Table 2.5). For example, potassium feldspar may contain almost 17% K_2O , but the dissolution is 20 million times slower than nepheline, a less abundant K-bearing mineral with 15% K_2O (Palandri and Kharaka 2004). The rate of K dissolution is key to its value as a source of plant nutrition (Manning 2018).

Considerable research has been conducted on developing various K-bearing minerals as fertilizers by utilizing a range of techniques to accelerate their dissolution through chemical or biological processes. The costs of transporting relatively low K concentration minerals often restricts their use to agricultural fields close to where they are mined.

The idea of using high K-content silicate rocks for fertilizer has been explored for many years (Ciceri et al. 2015), but most of the proposed techniques require significant energy or chemical inputs to accomplish a partial or complete dissolution of the rock. Based on dissolution rates of mineral K sources, rocks containing nepheline (including nepheline syenites, phonolites, and trachytes) may have the most commercial potential as agricultural potash sources (Manning 2010). Recent activity has focused on using K-rich feldspar as a nutrient source by milling, pH adjustment, and heating to accelerate natural weathering processes (Ciceri et al. 2016).

Glaucinite (greensand) is a relatively insoluble silicate-based marine sediment (5–8% K_2O) that has been used with limited success as a rock-based K source that dissolves over multiple years. Similarly, a variety of K-rich micas and feldspars have been evaluated for direct soil application as a K source with limited commercial success due to their low solubility. A fine particle size (“rock dust”) is required to allow dissolution at a rate that might provide a nutritional benefit for plants.

Table 2.5 Chemical composition and solubility in pure water for common K-bearing minerals. (adapted from Palandri and Kharaka 2004; Manning 2010)

Mineral	Mineral	Formula	Composition		Relative Solubility
			% K	% K_2O^a	
K feldspar	Feldspar	$KAlSi_3O_8$	14	16	Very low
Leucite	Feldspathoid	$KAlSi_2O_6$	17	21	Medium
Nepheline	Feldspathoid	$(K, Na)AlSiO_4$	13	15	Medium
Muscovite	Mica	$KAl_3Si_3O_{10}(OH)_2$	9	10	Very low
Biotite	Mica	$K_2Fe_6Si_6Al_2O_{20}(OH)_4$	7	9	Low
Phlogopite	Mica	$K_2Mg_6Si_6Al_2O_{20}(OH)_4$	9	11	Low
Glaucinite	Mica	$(K, Na)(Mg, Fe^{2+})(Fe^{3+}, Al)(Si, Al)_4O_{10}(OH)_2$	1–4	1–6	Medium

^aAll values rounded down to the nearest whole number

Other sources were used to verify, but not cited; there are several ways to express the formulas for each mineral, etc.

Interest in biological additives to solubilize K from insoluble minerals has grown. Addition of various bacteria and fungi have been evaluated as a means for accelerating dissolution of K-bearing minerals or chelating silicon ions to enhance K solubility (Meena et al. 2016). Many of these chemical and biological approaches of facilitating K release from relatively insoluble minerals have attracted considerable attention, especially in regions where the cost of soluble K fertilizers poses a barrier to use.

The long-term impacts of using native minerals as sources of K for plant growth are not yet known. As an example, the release of K from the interlayers of micas can result in the formation of vermiculites in very short time periods (Hinsinger et al. 1992). Vermiculites have a high selectivity for K (Evangelou and Lumbanraja 2002), resulting in a significant portion of applied K ending up in interlayer positions where it is unavailable to plants, reducing its apparent recovery efficiency (RE_K). To overcome the reduction in RE_K , larger quantities of K fertilizer must be applied to achieve the same quantity of plant-available K (Chap. 1; Cassman et al. 1989). Future investigations will need to consider how the removal of K from minerals impacts the effectiveness of future K fertilizer applications.

2.7.2.10 Other Potassium Sources

Other K-containing materials have long been used as plant nutrients. Seaweed kelp (2–4% K_2O) has a long history as a K fertilizer. Wood ash (2–9% K_2O) has also been traditionally applied to supply additional K to crops. The alkaline nature of wood ash (containing $CaCO_3$ or CaO) needs to be considered if ash is added to soil at high application rates or repeatedly over long periods. The nature of the fuel and the combustion conditions will influence the K bioavailability in the ash. Biochar is typically applied to soils for agronomic and environmental benefits. Biederman and Harpole (2013) conducted a meta-analysis of 114 published manuscripts and found that biochar application significantly increased plant K concentration as well as soil test K levels.

A variety of harvested crop materials are returned to the field after processing (such as pomace and bagasse) to recycle organic material and nutrients, including K. If crop residues are allowed to remain in the field after harvest or are returned to the soil after processing, they quickly release any remaining cellular K, where it is recycled into the soil with rain and becomes available for uptake by succeeding crops.

Many wastewaters and food processing residuals contain K. Applications of large quantities of K-containing waste should consider the potential effects on soil mineralogy, soil cation ratios, soil physical properties (Oster et al. 2016), potential K leaching losses, and the overall nutrition of crops growing on the site (Arienzo et al. 2009).

2.7.3 *Forms of Potassium Fertilizer*

Commercial fertilizer comes in many forms. These include bulk blends of individual solid fertilizer products, complex granules, and fluids.

2.7.3.1 Bulk Blends

Most K fertilizer is mechanically blended with other solid fertilizers to make a mix of desired nutrients. This approach of blending separate components not only has the advantage of allowing various single materials to be selected based primarily on the cost of the separate components, but also achieves specific physical, nutritional, and chemical properties desired by the farmer. Freight costs associated with transporting individual solid fertilizers are usually less than transporting a variety of bagged materials or fluid fertilizers. A degree of flexibility is available to adjust the precise nutrient composition of the fertilizer blend according to specific crop and soil conditions.

When separate fertilizer materials are blended together, care needs to be taken to match the size of the raw materials to minimize separation (segregation) during transportation and field application. Proper blending of solid fertilizer materials takes experience and understanding of the individual components to be successful. This also involves selecting appropriate granular, crystalline, or prilled fertilizer materials with the proper particle size. The critical relative humidity needs to be considered as the fertilizer will absorb atmospheric moisture which will affect the storage life of blends. The critical relative humidity for common K fertilizers is relatively high, making them less susceptible to caking and clumping than many other solid fertilizer materials.

2.7.3.2 Complex (Compound) Granules

Potassium is commonly used in many complex fertilizers that are mixed with N, P, and other plant nutrients all within a single granule. There are a variety of processes for making these homogeneous fertilizers, but they have the advantage that they will not segregate during transport or application, and every granule delivers the same quantity and ratio of nutrients. This can be particularly important when very low rates of nutrients, for instance, micronutrients, need to be applied uniformly across the field or in a band. The K portion of the granules is most commonly derived from KCl, which readily dissolves in the soil and quickly becomes available for plant uptake.

2.7.3.3 Fluid Fertilizers

Solution fertilizers are preferred by some farmers. They are relatively easy to blend, are homogeneous, and can be applied in a variety of ways. When fertigating, fluid fertilizers provide a convenient way to introduce nutrients directly into the irrigation water for delivery to crops. Solid K fertilizers can also be dissolved to create fluids and then subsequently used in similar ways.

2.7.4 Potassium for Fertigation

Nutrients added to a pressurized irrigation system should be fully dissolved before adding them into the water stream. Although most common K fertilizers are relatively soluble, users should be aware of the differences between materials. The presence of impurities, fertilizer coatings, and conditioners can cause problems with plugging of the irrigation system, so these materials must be removed by a filter or avoided by using high-purity fertilizer products. The most common sources for fertigation are KCl, K_2SO_4 , KNO_3 , $K_2S_2O_8$, and KH_2PO_4 . The selection of a particular K source is generally based on price, solubility, and the accompanying anion.

Choosing a specific K fertilizer for fertigation should account for potential chemical reactions between mixed fertilizers and the quality of the irrigation water. For example, the precipitation of calcium or phosphate salts in the irrigation lines can be minimized by selecting appropriate K fertilizer sources. Potassium itself is not generally a problem during fertigation, but the potential reactions of the accompanying anions need to be considered to avoid plugging the irrigation system.

2.7.5 Salt Index

Any soluble fertilizer will act as a salt when dissolved, thereby increasing the osmotic potential of the soil solution. The concept of “salt index” was first developed to predict the safety of a fertilizer placed in the proximity to a seedling (Rader et al. 1943). As various protocols have been developed to measure the safety of fertilizers placed near seeds and roots, it has been shown that other factors such as the crop and soil type, soil temperature and moisture, and fertilizer application rate have an equally or more important impact on potential seedling damage than the salinity developed while the fertilizer dissolves (Mortvedt 2001).

The original method for measuring salt index (Rader et al. 1943) was modified by Jackson (1958) and then again by Murray and Clapp (2004). Unfortunately, the different methods give inconsistent rankings in their prediction of potential salt damage. Additionally, the ranking of salt index reported for K fertilizers also varies

in commonly used reference books. The use of salt index values does not predict the amount of fertilizer that will cause plant damage, but instead is most useful for providing a relative ranking of materials. In cases such as fertigation and foliar applications of K, the dilution of nutrients in relatively large quantities of water makes the salt index values less applicable. For example, Jifon and Lester (2009) used six K sources (KCl , KNO_3 , KH_2PO_4 , K_2SO_4 , $\text{K}_2\text{S}_2\text{O}_3$, and a glycine amino-acid complexed K) as a foliar spray on musk melon (*Cucumis melo* L.) and found no differences in plant damage from any source or concentrations, with the solution buffered between pH 6.5 and 7.7.

The salt index of fertilizer is usually greatest for soluble N and K sources, indicating that it is usually best to avoid placement of large quantities close to the newly planted seed. A decision tool has been developed to help calculate the maximum amount of fertilizer that can be safely placed near seeds (SDSU and IPNI 2019). There is frequently little advantage for plant growth derived from placing fertilizer K very near the seed (unlike N and P) compared to the bulk soil. Damage to emerging seeds and seedlings from furrow-placed fertilizer can be minimized by avoiding high application rates of K.

2.7.6 Chloride Considerations

As mentioned previously, the selection of a particular source of K fertilizer is sometimes based on whether it contains Cl. There is a wide range of Cl sensitivity among plant species and cultivars. As a broad classification, many woody plant species, vegetables, and beans are more susceptible to Cl toxicity, whereas many non-woody crops tolerate higher concentrations of Cl^- in the root zone (Maas 1986).

There is a large body of literature related to the effects of Cl^- on crop performance (Xu et al. 2000). Chloride is an essential plant nutrient, and it is routinely added in some environments to enhance plant growth and disease resistance (Chen et al. 2010). However, excessively high Cl^- concentrations are linked to decreased crop growth and quality due to osmotic effects and specific ion toxicity.

To illustrate the difficulty in generalizing chloride's effects, we highlight some of the research on potatoes (*Solanum tuberosum* L.). Potatoes are an important crop that are rated as moderately sensitive to root zone salinity (Maas 1986). The effect of K fertilizer source on potato growth and quality has likely received more attention than any other crop. Potatoes accumulate large amounts of K during the growing season ($>600 \text{ kg K ha}^{-1} \text{ year}^{-1}$; Horneck and Rosen 2008) and frequently receive K fertilizer to sustain high yields. There are reports of an undesirable reduction in specific gravity (% dry matter) in potatoes receiving various K fertilizers. Some researchers have observed no differences in potato specific gravity when comparing various K fertilizer sources, while others have measured a decrease in specific gravity when using KCl compared with K_2SO_4 (e.g., Davenport and Bentley 2001). This reduction in specific gravity may not be directly due to the presence of

Cl^- but to greater K uptake from KCl and a higher salt index. These factors may cause the tubers to absorb more water than when fertilized with another K source.

Other research shows that the total K application rate has a greater impact on reducing specific gravity of tubers than the individual K fertilizer source (Westerman et al. 1994). Additionally, when KCl is split into multiple applications, or if KCl is applied in the autumn (with adequate winter rain) for a spring-planted potato crop, any negative impact on specific gravity is eliminated. Factors such as the climate and the potato variety can also influence the effect of K fertilization on potato specific gravity (Hütsch et al. 2018). These many interacting factors illustrate the difficulty in generalizing about selecting the proper K source for all conditions.

Differences in crop tolerance to Cl^- clearly exist. Although general osmotic damage can occur to germinating seeds and growing plants, there are also specific ion effects that can harm plants. For example, Tinker et al. (1977) reported that KCl fertilizer caused more damage to germinating seedlings than KNO_3 , although the damage varied widely among the five plant species tested. They also reported that the fertilizer concentration, soil water content, and temperature also impacted the degree of seedling damage. Differences in the ability of species and cultivars to tolerate Cl^- stress are often related to the ability to restrict Cl uptake to the plant shoot (White and Broadley 2001).

The sensitivity of crops to salinity will change during the growing season, with young and newly developing seedlings generally most susceptible to salt damage. Once established, most crops become increasingly tolerant to salinity. In general practice, when application rates of KCl are not excessive or KCl is blended with another K source, no plant damage from excessive Cl^- is usually observed. In many situations, the amount of Cl added to a field as KCl is often small compared with the total amount of Cl already present in the soil and added as irrigation water. If KCl is applied in a localized band or zone in the soil, the initial soluble Cl concentration will spike and then decrease as Cl moves from the band into the surrounding soil by diffusion and mass flow.

2.7.7 Foliar Potassium Nutrition

Most crops have a relatively high demand for K throughout the growing season. If K uptake from the soil does not meet the plant demand, then growth, yield, and quality will suffer (Mikkelsen 2017). In the case where K uptake is insufficient, spraying an aqueous K-containing solution directly onto the plant foliage often overcomes this deficiency.

Applications of K-containing sprays directly onto the foliage of annual and perennial crops are common. Fernandez et al. have made several insightful reviews on this topic (Fernández and Brown 2013; Fernández et al. 2013). This practice is frequently done on high-value vegetables (e.g., Gunadi 2009; Jifon and Lester 2009; Salim et al. 2014) and perennial crops (e.g., Ben Yahmed and Ben Mimoun 2019; Shen et al. 2016; Solhjoo et al. 2017).

A foliar application of K during the growing season has been shown to improve crop yield and quality in many situations. Some plants have a high physiological K demand during specific stages of their growth cycle. For example, cotton (*Gossypium hirsutum* L.) is routinely sprayed with a foliar K solution in order to boost lint yield and quality during the late stage of crop development (Oosterhuis et al. 2014).

Crops frequently benefit from foliar K sprays if the soil-supplying capacity is too low (e.g., lack of proper fertilization) or if soil conditions do not permit uptake of soluble K by the roots (e.g., cold temperature, drought, water logging, nematodes, etc.). In these circumstances, a relatively small amount of K applied directly to the foliage can make a significant improvement to crop health and growth.

Foliar fertilization is common when tissue testing or observation of visual symptoms identifies an emerging K deficiency. Prompt correction of the K deficiency can halt additional damage, since foliar-applied K is rapidly taken up through the leaves and quickly utilized in the plant (Fageria et al. 2009). Application of the dilute K fertilizer solution can be done using a variety of spray equipment (such as an airblast-type sprayer) to deliver K onto crop leaves to supplement the soil supply. Potential benefits achieved from an intervention with a foliar spray need to be weighed against the financial costs of the field operation. Foliar K applications often occur while other chemicals are being sprayed on the plants to minimize the number of trips through the field.

Although foliar K sprays are beneficial in many situations, the majority of plant K is acquired and taken up by the roots. A foliar K fertilization program should be viewed as a supplement to maintaining an adequate concentration of soluble K in the soil. For example, Gordon and Niederholzer (2019) explain that a typical application to almond foliage of $27 \text{ kg KNO}_3 \text{ ha}^{-1}$ ($\sim 10 \text{ kg K ha}^{-1}$) in 1000 L will likely result in an increased leaf K concentration. However, this single application will only provide about 3% of the total crop K requirement (assuming a spray application efficiency of 75%). Clearly this relatively small amount of K added through foliar fertilization is merely a supplement to the soil supply, even when multiple applications are made through the growing season.

Repeated applications of foliar K solutions with a high concentration of fertilizer salt often leads to leaf damage (“salt burn”). Therefore, advice should be sought before beginning a foliar fertilization program in order to identify the appropriate 4R-based practices (Right Source, Right Rate, Right Time, and Right Place) suited to a specific crop and agro-environment.

Although KCl is the most common K fertilizer applied to soil, it has a high salt index (osmotic potential) and point of deliquescence (POD; crystallization) that may limit its use in foliar sprays. There are several excellent K fertilizer sources that are used for foliar nutrition. The most common of these are K_2SO_4 , KNO_3 , KH_2PO_4 , and organic-based formulations.

2.8 Summary

Accounting for all K inputs is difficult to do accurately. Most inputs, except commercial fertilizers, have variable K contents that are not routinely measured on the farm. Testing those inputs for their content is preferred, but standardized values can be used as a substitute. The emphasis of this chapter has been on commercial fertilizers. These inputs are produced from K-bearing minerals found around the world. Reserves have an expected lifetime of thousands of years. When a need for additional K for plant growth has been identified, there are many sources of fertilizer that can be used to meet nutritional requirements. The selection of a specific potash fertilizer source largely depends on the nutrients that accompany the K, the fertilizer's availability in the market, and its price. As new technology is introduced, the importance of less-soluble K-bearing minerals as a plant nutrient source may increase, especially in regions of the world where soluble K fertilizers are not accessible or are too expensive for farmers. There are many factors to consider in selecting the most appropriate K source. Whatever source is selected, the soluble K^+ is the same for nutrition of the plant. It is essential that an adequate concentration of plant-available K is maintained in the rootzone to produce abundant and high-quality crops.

References

- American Meteorological Society (2012) Dry deposition. Glossary of meteorology. <http://glossary.ametsoc.org/wiki/climatology>. Accessed 08 May 2020
- Arienzo M, Christen EW, Quayle W, Kumar A (2009) A review of the fate of potassium in the soil-plant system after land application of wastewaters. *J Hazard Mater* 164:415–422. <https://doi.org/10.1016/j.jhazmat.2008.08.095>
- Barbier M, Li YC, Liu G, He Z, Mylavarapu R, Zhang S (2017) Characterizing polyhalite plant nutritional properties. *Agric Res Technol* 6(3). <https://doi.org/10.19080/ARTOAJ.2017.06.555690>
- Ben Yahmed J, Ben Mimoun M (2019) Effects of foliar application and fertigation of potassium on yield and fruit quality of 'Superior Seedless' grapevine. *Acta Hort* (1253):367–372. <https://doi.org/10.17660/ActaHortic.2019.1253.48>
- Biederman LA, Harpole WS (2013) Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. *BCB Bioenergy* 5:202–214. <https://doi.org/10.1111/gcbb.12037>
- Cai Z, Gao S, Xu M, Hanson BD (2018) Evaluation of potassium thiosulfate as a nitrification inhibitor to reduce nitrous oxide emissions. *Sci Total Environ* 618:243–249. <https://doi.org/10.1016/j.scitotenv.2017.10.274>
- Cassman KG, Roberts BA, Kerby TA, Bryant DC, Higashi SL (1989) Soil potassium balance and cumulative cotton response to annual potassium additions on a vermiculitic soil. *Soil Sci Soc Am J* 53:805–812. <https://doi.org/10.2136/sssaj1989.03615995005300030030x>
- Chen W, He ZL, Yang XE, Mishra S, Stoffella PJ (2010) Chlorine nutrition of higher plants: progress and perspectives. *J Plant Nutr* 33(7):943–952. <https://doi.org/10.1080/01904160903242417>
- Ciceri D, Manning DAC, Allanore A (2015) Historical and technical developments of potassium resources. *Sci Total Environ* 502:590–601. <https://doi.org/10.1016/j.scitotenv.2014.09.013>

- Ciceri DT, Skorina C, Gadois K, Li, Allanore A (2016) Processing of potassium silicates for K-release. In: de Melo Benites V, de Oliveira Junior A, Pavinato PS, Teixeira PC, Moraes MF, de Campos Leite RMVB, de Oliveira RP (eds) Proceedings of 16th world fertilizer congress of CIEC, pp 102–104
- Darmody RG, Ruiz D (2017) Dredged sediment: application as an agricultural amendment on sandy soils. Illinois Sustainable Technol Center TR-066. <http://hdl.handle.net/2142/97824>. Accessed 08 May 2020
- Davenport JR, Bentley EM (2001) Does potassium fertilizer form, source, and time of application influence potato yield and quality in the Columbia Basin? Am J Potato Res 78:311–318. <https://doi.org/10.1007/BF02875696>
- Duo Z, Galligan DT, Allshouse RD, Toth JD, Ramberg CF, Ferguson JD (2001) Manure sampling for nutrient analysis. J Environ Qual 30(4):1432–1437. <https://doi.org/10.2134/jeq2001.3041432x>
- Evangelou VP, Lumbanraja J (2002) Ammonium-potassium-calcium exchange on vermiculite and hydroxy-aluminum vermiculite. Soil Sci Soc Am J 66:445–455. <https://doi.org/10.2136/sssaj2002.4450>
- Fageria NK, Barbosa Filho MP, Moreira A, Guimaraes CM (2009) Foliar fertilization of crop plants. J Plant Nutr 32:1044–1064., 2009. <https://doi.org/10.1080/01904160902872826>
- Fernández V, Brown PH (2013) From plant surface to plant metabolism: the uncertain fate of foliar-applied nutrients. Front Plant Sci 4:289. <https://doi.org/10.3389/fpls.2013.00289>
- Fernández V, Sotiropoulos T, Brown P (2013) Foliar fertilization: scientific principles and field practices. IFA, Paris
- Fountain DM, Christensen NI (1989) Composition of the continental crust and upper mantle; A review. In: Pakiser LC, Mooney WD (eds) Geophysical framework of the continental United States. Geol Soc Am Mem 172:711–742. <https://doi.org/10.1130/MEM172-p711>
- Goos RJ, Johnson BE (2001) Thiosulfate oxidation by three soils as influenced by temperature. Commun Soil Sci Plan 32(17–18):2841–2849. <https://doi.org/10.1081/CSS-120000966>
- Gordon P, Niederholzer FJA (2019) Potassium in nut crops? Plant uses and field applications. <https://www.sjvtandv.com/blog/kgkt2owv6lxnrb1o4i15lmfipj9y4w>. Accessed 01 June 2020
- Gunadi N (2009) Response of potato to potassium fertilizer sources and application methods in Andisols of West Java. Indones J Agric Sci 10(2):65–72
- Harley GT, Atwood GE (1947) Langbeinite. . mining and processing. Ind Eng Chem 39(1):43–47. <https://doi.org/10.1021/ie50445a020>
- Hinsinger P, Jaillard B, Dufey JE (1992) Rapid weathering of a trioctahedral mica by the roots of ryegrass. Soil Sci Soc Am J 56:977–982. <https://doi.org/10.2136/sssaj1992.03615995005600030049x>
- Hoa NM, Janssen GH, Oenema O, Dobermann A (2006) Comparison of partial and complete soil K budgets under intensive rice cropping in the Mekong Delta, Vietnam. Agric Ecosyst Environ 116:121–131. <https://doi.org/10.1016/j.agee.2006.03.020>
- Horneck D, Rosen C (2008) Measuring nutrient accumulation rates of potatoes – tools for better management. Better Crops 92(1):4–6
- Hung NV, Maguyon-Debras MC, Migo MV, Quilloy R, Balingbing C, Chivenge P, Gummert M (2020) Rice straw overview: availability, properties, and management practices. In: Gummert M, Hung NV, Chivenge P, Douthwaite B (eds) Sustainable rice straw management. Springer, New York. https://doi.org/10.1007/978-3-030-32373-8_1
- Hütsch BW, Keipp K, Glaser A-K, Schubert S (2018) Potato plants (*Solanum tuberosum* L.) are chloride-sensitive: is this dogma valid? J Sci Food Agr 98(8):3161–3168. <https://doi.org/10.1002/jsfa.8819>
- IFDC, UNIDO (eds) (1998) Fertilizer manual. United Nations Industrial Development Organization and International Fertilizer Development Center, Kluwer Academic, Dordrecht
- IPNI (2012) 4R Plant nutrition manual: a manual for improving the management of plant nutrition. Metric version. In: Bruulsema TW, Fixen PE, Sulewski GD (eds) International Plant Nutrition Institute, Norcross

- Jackson WL (1958) Soil chemical analysis. Prentice Hall, Englewood Cliffs, NJ
- Jifon JL, Lester GE (2009) Foliar potassium fertilization improves fruit quality of field-grown muskmelon on calcareous soils in south Texas. *J Sci Food Agr* 89:2452–2460. <https://doi.org/10.1002/jsfa.3745>
- Junakova N, Balintova M (2012) Assessment of nutrient concentration in reservoir bottom sediments. *Procedia Eng* 42:165–170. <https://doi.org/10.1016/j.proeng.2012.07.407>
- Liptay A, Arevalo AE (2000) Plant mineral accumulation, use and transport during the life cycle of plants: a review. *Can J Plant Sci* 80:29–38. <https://doi.org/10.4141/P99-014>
- Liu L, Zhang X, Wang S, Zhang W, Lu X (2016) Bulk sulfur (S) deposition in China. *Atmos Environ* 135:41–49. <https://doi.org/10.1016/j.atmosenv.2016.04.003>
- Maas EV (1986) Salt tolerance of plants. *Appl Agric Res* 1:12–26
- Manning DAC (2010) Mineral sources of potassium for plant nutrition. A review. *Agron Sustain Dev* 30(2):281–294. <https://doi.org/10.1051/agro/2009023>
- Manning DAC (2018) Innovation in resourcing geological materials as crop nutrients. *Nat Resour Res* 27(2):217–227. <https://doi.org/10.1007/s11053-017-9347-2>
- Meena VS, Maurya BR, Verma P, Meena RS (eds) (2016) Potassium solubilizing microorganisms for sustainable agriculture. Springer, New Delhi. <https://doi.org/10.1007/978-81-322-2776-2>
- Miao Y, Stewart BA, Zhang F (2011) Long-term experiments for sustainable nutrient management in China. A review. *Agron Sustain Dev* 31(2):397–414. <https://doi.org/10.1051/agro/2010034>
- Mikha MM, Benjamin JG, Vigil MF, Poss DJ (2017) Manure use and tillage use in remediation of eroded land and impacts on soil chemical properties. *PLoS One* 12(4):e0175533. <https://doi.org/10.1371/journal.pone.0175533>
- Mikhailova EA, Post GC, Cope MP, Post CJ, Schlautman MA, Zhang L (2019) Quantifying and mapping atmospheric potassium deposition for soil ecosystem services assessment in the United States. *Front Environ Sci* 7:Article 74. <https://doi.org/10.3389/fenvs.2019.00074>
- Mikkelsen RL (2000a) Nutrient management for organic farming: a case study. *J Nat Resour Life Sci Ed* 29:88–92. <https://doi.org/10.2134/jnrlse.2000.0088>
- Mikkelsen RL (2000b) Beneficial use of swine by-products: Opportunities for the future. In: Powers J et al (eds) Beneficial uses of agricultural, industrial, and municipal by-products. Soil Science Society of America, Madison, pp 451–480. <https://doi.org/10.2136/sssabookser6.c16>
- Mikkelsen RL (2007) Managing potassium for organic crop production. *HortTechn* 17(4):455–460. <https://doi.org/10.21273/HORTTECH.17.4.455>
- Mikkelsen R (2017) The importance of potassium management for horticultural crops. *Indian J Fert* 13(11):82–86
- Mortvedt JJ (2001) Calculating salt index. *Fluid J Spring* 2001:1–3. <https://fluidfertilizer.org/33p8-11/>. Accessed 20 May 2020
- Murray TP, Clapp JG (2004) Current fertilizer salt index tables are misleading. *Commun Soil Sci Plan* 35(19–20):2867–2873. <https://doi.org/10.1081/CSS-200036474>
- National Agricultural Library (2019a) Atmospheric deposition. Term no. 2714, Agricultural thesaurus. <https://agclass.nal.usda.gov/agt.shtml>. Accessed 20 May 2020
- National Agricultural Library (2019b) Wet deposition. Term no. 68066, Agricultural thesaurus. <https://agclass.nal.usda.gov/agt.shtml>. Accessed 20 May 2020
- Nayak S, Dash A (2006) Oxidation of the thiosulfate ion by some iron(III) complexes with phenolate – amide-amine coordination: a comparative kinetic study. *Transit Metal Chem* 31:930–937. <https://doi.org/10.1007/s11243-006-0086-1>
- O'Dell JD, Essington ME, Howard DD (1995) Surface application of liquid swine manure: chemical variability. *Commun Soil Sci Plan* 26(19–20):3113–3120. <https://doi.org/10.1080/00103629509369513>
- Oosterhuis DM, Loka DA, Kawakami EM, Pettigrew WT (2014) The physiology of potassium in crop production. *Adv Agron* 126:203–233. <https://doi.org/10.1016/B978-0-12-800132-5.00003-1>
- Orris GJ, Cocker MD, Dunlap P, Wynn J, Spanski GT, Briggs DA, Gass L, with contributions from Bliss JD, Bolm KS, Yang C, Lipin BR, Ludington S, Miller RJ, Slowakiewicz M (2014)

- Potash—a global overview of evaporate-related potash resources, including spatial databases of deposits, occurrences, and permissive tracts. U.S. Geological Survey scientific investigations report 2010–5090-S. <https://doi.org/10.3133/sir20105090S>
- Oster JD, Sposito G, Smith CJ (2016) Accounting for potassium and magnesium in irrigation water quality assessment. *Calif Agr* 70(2):71–76. <https://doi.org/10.3733/ca.v070n02p71>
- Palandri JL, Kharaka YK (2004) A compilation of rate parameters of water-mineral interaction kinetics for application to geochemical modeling. U.S. Geological Survey, open file report 2004–1068. <https://pubs.usgs.gov/of/2004/1068>. Accessed 8 May 2020
- Pan YP, Wang YS (2015) Atmospheric wet and dry deposition of trace elements at 10 sites in Northern China. *Atmos Chem Phys* 15:951–972. <https://doi.org/10.5194/acp-15-951-2015>
- Prospero JM, Collard FX, Molinie J, Jeannot A (2014) Characterizing the annual cycle of African dust transport to the Caribbean Basin and South America and its impact on the environment and air quality. *Glob Biogeo Cycl* 28:757–773. <https://doi.org/10.1002/2013GB004802>
- Rader LF Jr, White LM, Whittaker CW (1943) The salt index – a measure of the effect of fertilizers on the concentration of the soil solution. *Soil Sci* 55(3):201–218. <https://journals.lww.com/soilsci/toc/1943/03000>. Accessed 8 May 2020
- Rahm M (2017) The global potassium market. In: Murrell TS, Mikkelsen RL (eds) Proceedings of frontiers potassium science conference, Rome, 25–27 Jan 2017. International Plant Nutrition Institute, Peachtree Corners. <https://www.apni.net/k-frontier.org>. Accessed 8 May 2020
- Ruscio A, Kazanc F, Levendis YA (2016) Comparison of fine ash emissions generated from biomass and coal combustion and valuation of predictive furnace deposition indices: a review. *J Energ Eng* 142:E4015007. [https://doi.org/10.1061/\(ASCE\)EY.1943-7897.0000310](https://doi.org/10.1061/(ASCE)EY.1943-7897.0000310)
- Salim BBM, Abd El-Gawad HG, Abou El-Yazied A (2014) Effect of foliar spray of different potassium sources on growth, yield and mineral composition of potato (*Solanum tuberosum* L.). *Middle East J Appl Sci* 4:1197–1204
- SDSU, IPNI (2019) Seed damage calculator. South Dakota Cooperative Extension Service and the International Plant Nutrition Institute. <http://seed-damage-calculator.herokuapp.com>. Accessed 08 May 2020
- Sheldrick WF (1985) World potassium reserves. In: Munson RD (ed) Potassium in agriculture. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, pp 3–28. <https://doi.org/10.2134/1985.potassium.c1>
- Shen C, Ding Y, Lei X, Zhao P, Wang S, Xu Y, Dong C (2016) Effects of foliar potassium fertilization on fruit growth rate, potassium accumulation, yield, and quality of ‘Kousui’ Japanese Pear. *HortTechnology* 26:270–277. <https://doi.org/10.21273/HORTTECH.26.3.270>
- Smith SJ, van Aardenne J, Klimont Z, Andres RJ, Volke A, Arias SD (2011) Anthropogenic sulfur dioxide emissions: 1850–2005. *Atmos Chem Phys* 11:1101–1116. <https://doi.org/10.5194/acp-11-1101-2011>
- Solhjoo S, Gharaghani A, Fallahi E (2017) Calcium and potassium foliar sprays affect fruit skin color, quality attributes, and mineral nutrient concentrations of ‘red delicious’ apples. *Int J Fruit Sci* 17:358–373. <https://doi.org/10.1080/15538362.2017.1318734>
- SOPIB (Sulfate of Potash Information Board) (2015) The use of potassium sulfate fertilizer: principles and practices
- Tinker PB, Reed L, Legg C, Højer-Pederson S (1977) The effects of chloride in fertiliser salts on crop seed germination. *J Sci Food Agric* 28(12):1045–1051. <https://doi.org/10.1002/jsfa.2740281202>
- U.S. Bureau of Mines, U.S. Geological Survey (1980) Principles of a resource/reserve classification for minerals. Geological Survey Circular 831. <https://pubs.usgs.gov/circ/1980/0831/report.pdf>. Accessed 08 May 2020
- U.S. Geological Survey (USGS) (2020) Mineral commodity summaries 2020: U.S. Geological Survey. <https://doi.org/10.3133/mcs2020>
- Westerman DT, Tindall TA, James DW, Hurst RL (1994) Nitrogen and potassium fertilization of potatoes: yield and specific gravity. *Am Potato J* 71(7):417–431. <https://doi.org/10.1007/BF02849097>

- White PJ, Broadley MR (2001) Chloride in soils and its uptake and movement within the plant: a review. *Ann Bot-Lond* 88(6):967–988. <https://doi.org/10.1006/anbo.2001.1540>
- Williams M (2012) River sediments. *Philos Trans R Soc A* 370:2093–2122. <https://doi.org/10.1098/rsta.2011.0504>
- Williams PH, Gregg PEH, Hedley GM (1990) Fate of potassium in dairy cow urine applied to intact soil cores. *New Zealand J Agric Res* 33:151–158. <https://doi.org/10.1080/00288233.1990.10430672>
- Woodard HJ (1999) Plant growth on soils mixed with dredged lake sediment. *J Environ Sci Health A* 34:1229–1252. <https://doi.org/10.1080/10934529909376893>
- Xu G, Magen H, Tarchitzky J, Kafkafi U (2000) Advances in chloride nutrition of plants. *Adv Agron* 68:97–150. [https://doi.org/10.1016/S0065-2113\(08\)60844-5](https://doi.org/10.1016/S0065-2113(08)60844-5)
- Yermiyahu U, Zipori I, Faingold I, Yusopov L, Faust N, Bar-Tal A (2017) Polyhalite as a multi nutrient fertilizer potassium, magnesium, calcium and sulfate. *Israel J Plant Sci* 64 (3–4):145–157. <https://doi.org/10.1163/22238980-06401001>
- Zhang H, Wang B, Xu M, Fan T (2009) Crop yield and soil responses to long-term fertilization on a red soil in southern China. *Pedosphere* 19:199–207
- Zhang Y, Mathur R, Bash JO, Hogrefe C, Xing J, Roselle SJ (2018) Long-term trends in total inorganic nitrogen and sulfur deposition in the US from 1990 to 2010. *Atmos Chem Phys* 18:9091–9106. <https://doi.org/10.5194/acp-18-9091-2018>

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.