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Review

A review of the fate of potassium in the soil–plant system after land application of wastewaters

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ABSTRACT

Irrigation with wastewaters from agri-industry processes such as milk factories, piggeries, wineries and abattoirs is commonplace. These wastewaters all have high levels of potassium (K). Potassium concentration in effluents from domestic wastewater sources are relatively low, reported to vary between 10 and 30 mg L^{-1}. Higher levels of potassium are reported for effluents from olive oil mills, 10,000–20,000 mg K L^{-1}, wool scouring, 4200–13,000 mg K L^{-1}, cheese and lactic whey and potato processing, ~1800 mg K L^{-1}, piggery effluent, 500–1000 mg K L^{-1} and winery wastewaters, up to 1000 mg K L^{-1}. Application of wastewaters with these high potassium levels has been found to increase the overall level of soil fertility, with the exception of alkaline effluents which can dissolve soil organic carbon. Long-term application of such wastewater may cause the build-up of soil potassium and decrease the hydraulic conductivity of the receiving soils. These potential impacts are uncertain and have been inadequately researched. Regulatory limits for potassium in drinking water have been set only by the European Union with no toxicological or physiological justification. The literature shows that grasses and legume herbages accumulate high levels of potassium, up to 5% dry weight, and some grasses, such as turfgrass are particularly tolerant to high levels of potassium, even under saline conditions. This adaptation is considered useful for increasing potassium immobilization and sustainable practices of land wastewater disposal. Potassium availability is significantly affected by the cation ratios of the wastewater, the existing soil water solution and of soil exchange sites.

Contents

1. Introduction

Wastewaters from urban and agricultural sources have great potential for re-use as sources of water, organic matter, nutrients and soil conditioning agents [1]. The organic matter in these materials can improve soil aeration, increase water infiltration and soil moisture holding capacity, decrease soil erosion potential, increase soil cation exchange, buffer soil pH and promote the growth of beneficial soil organisms. However, the use of wastewater can also have negative effects such as increased soil salinity, undesirable pH values, anaerobic conditions in the root zone and excessive leaching of nutrients and heavy metals.

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Table 1
Potassium and sodium concentration in municipal and agricultural sewage effluents

Water source	K concentration (mg L^{-1})	Na concentration (mg L^{-1})	References
Municipal	13–20	50–250	[7–9]
Milk powder/butter factory	13	560	[5,8]
Cheese whey	1,680		[5,8]
Lactic/casein whey	1,660		[5,8]
Slaughterhouse	90		[5,8]
Fellmongery	50		[5,8]
Meat processing	20–150	50–250	[5,8]
Dairy shed	220	50	[5,8]
Piggery	500–1000	320	[13]
Winery	250	130	[20]
Olive oil processing	10,000–200,000	160–400	[14]
Palm oil processing	2,100	80–120	[15]

Table 2
Analytical results for selected waste streams collected in the Melbourne metropolitan area [12]

Industry waste	K (mg L^{-1})	N (mg L^{-1})	P (mg L^{-1})
Wool/sludge	4,200	8,400	600
Wool/fibres	13,800	26,000	1,500
Tannery/sludge	700	12,000	3,300
Tannery/sludge (Cr)	1,100	7,900	<600
Tannery/sludge (fatty)	<400	6,700	<600
Tannery/hair	<400	49,500	<600
Food waste/beans	<400	9,300	600
Potato waste	1,800	1,200	<600

The availability and use of wastewater for irrigation has increased as availability of other irrigation water becomes more limited and the disposal of wastewaters into waterways becomes more restricted. The availability of wastewater as well as the nutrients it may contain make it an attractive source for irrigation with potential fertilizer cost savings.

Much of the research on the environmental impact of nutrients contained in wastewaters has involved inorganic forms of phosphorous (ortho-P) and nitrogen (NH_4–N and NO_3–N) at concentrations representative of fertilizer application [2], and in the reuse of sewage effluent [3]. Potassium is ubiquitous in wastewaters and in some wastewaters is present at several hundred to several thousand mg L^{-1}. The current trend for substitution of sodium hydroxide with potassium hydroxide as a caustic cleaning and disinfection chemical in the operational processes of many industries such as wineries has also the potential to further increase potassium levels in wastewater. Thus, potassium accumulation in soils is seen by industry and regulators as a potential problem because of the effect it might have on salt accumulation and soil structure. These effects at the present are unclear since very few studies exist. The processes that control the fate of potassium in soils deriving from land waste disposal are complex and many of them are poorly understood, e.g. the rate of potassium release, leaching, as well the long-term plant bioavailability.

Irrigation with wastewaters may result in potassium availability that can correspond to or be in excess to plant requirements. Potassium in addition to its many biochemical functions improves the tolerance of the plant to various stress situations, such as drought, low temperature or salinity [3,4].

In this review we report the levels of potassium in municipal and agricultural wastewaters, the main factors affecting plant potassium availability at wastewater disposal sites and its uptake by plants.

2. Potassium levels in wastewaters

A wide variety of wastewaters are produced which contain potassium. These can be from dairy sheds and milk processing factories, piggeries, chicken farms and processing plants, meat processing plants, fellmongeries, fish processing plants, timber processing plants, wool scours, feedlots, vegetable processing plants, wineries, paper and printing operations, textile plants, metal industries, and sewage treatment plants [5,6]. Some examples of the potassium and sodium contents of these wastes are given in Table 1. The wide range of chemical, physical, and biological characteristics of these wastes makes it difficult to develop guidelines for their use. The chemical composition not only varies between the various waste streams but also varies with time and with treatment of the individual waste stream. A lot of attention has traditionally been paid to nitrogen, phosphorous and organic matter in wastewater for reuse. These elements can be controlled/treated by typical aerobic and anaerobic treatment processes. The levels of potassium have received less attention and are not reduced during typical treatment processes, in fact the concentration often increases due to evaporation from wastewater treatment and storage ponds.

Potassium concentrations in sewage effluent are quite low. Pettygrove et al. [7] gave ranges for the potassium concentration in sewage waters and effluents. The average potassium concentration in sewage water was 15 mg L^{-1} in New Mexico, 12 mg L^{-1} in Frankston (Australia) and 15–30 mg L^{-1} in Alberta (Canada) [6]. A value of 24 mg K L^{-1} in sewage water was reported in Israel [8]. The average potassium content in the sewage effluents reported by Emongor and Ramolemana [9] is 25 mg L^{-1}. Thus, it seems that potassium concentration in effluents and sewage from domestic sources are in the order of 10–30 mg L^{-1}. The concentrations result, in part, from accumulation during domestic water use, additions of potassium of 7–15 mg L^{-1} are reported for California [10] and 18.8 mg L^{-1} in Israel [8].

Meehan et al. [11] reported the analytical results for selected waste streams collected in the Melbourne (Australia) metropolitan area, which were analysed to identify possible nutrient sources and contaminants (Table 2). The authors found that many of the effluents have high potassium levels and the effluent generated by the wool scouring process, called suint, has a very high potassium content indeed, 13,800 mg L^{-1}.

Wastewater from piggeries often contains very high concentrations of potassium, up to 1000 mg L^{-1} and levels of N and P of 750 mg L^{-1} [12].

Winery wastewater is highly variable, and its characteristics are known to fluctuate markedly with size of winery, treatment processes as well as the season (pre-vintage, vintage and post vintage). Grape juice has a potassium concentration ranging between 2000 and 3000 mg L^{-1} and is the major contributor to the high potassium levels in winery wastewater. Cleaning products such as potassium hydroxide used in the winery processes also contribute to the potassium load. Depending on seasonal fluctuations due to harvesting and crush operations in the vintage period, potassium contents in wastewater can range between 315 ± 85 mg L^{-1} in a small (200 tonnes annual crush) winery to 150 ± 9 mg L^{-1} in a large winery (25,000 tonnes annual crush). However, the concentration of potassium in winery wastewaters can go up to 1000 mg L^{-1} during the vintage season. Like winery wastewaters, olive oil mill wastewaters (OMWW) can be highly polluting due to their high organic content, especially polyphenolic mixtures and acidity. OMWW contain also high concentrations of potassium, magnesium and phosphate salts [13]. Levels of potassium in samples of OMWW can be close to 18,000 mg L^{-1} [13]. Most of the potassium was found to be adsorbed to the negative charge of the organic polymeric fraction composed of polysaccharides, phenol polymers and proteins. Palm oil mill effluent (POME) also has a very high potassium content, Ma et al. [14] report values of 2116 mg L^{-1}.

Table 3
Volumes of irrigation water of different effluents to achieve an application rate of K as fertilizer of 130 kg ha^{-1}

Water source	K concentration (mg L^{-1})	Volume of irrigation water (m^3 ha^{-1})
Municipal	13–20	10,000–6,500
Primary effluent	13–33	10,000–3,940
Milk powder/butter factory wastewater	13	10,000
Cheese whey	1,680	77
Lactic/casein whey	1,660	78
Slaughterhouse	90	1,440
Fellmongery	50	2,600
Meat processing secondary effluents	20–150	6,500–870
Dairy shed	220	590
Piggery	500–1,000	260–130
Wineries	250	520
Olive oil	10,000–200,000	13–1
Palm oil	2,100	62

Apart from the concentration of potassium, the total loading to soil is important. The potassium contribution from treated municipal wastewater, based on a typical application rate of 5000 m^3 ha^{-1}, provides a potassium contribution of 130 kg ha^{-1} [15]. Fertilizer potassium application rates often range between 30 and 70 kg ha^{-1} [16], but they can be higher depending on soil type, crop and other environmental conditions. Therefore when irrigating crops with wastewater effluent the application of potassium fertilizer should be reduced. Table 3 reports the volumes of different effluents to achieve an application rate of potassium of 130 kg ha^{-1}. The volumes range between 10,000 and 13 m^3 ha^{-1} for municipal/milk factory and olive oil effluents.

3. The effect of potassium from wastewater disposal on soil fertility

Many studies have shown that the overall soil fertility is increased after land application of liquid and solid wastes [17,18]. Application of wastewaters has been shown to cause a significant increase in soil organic carbon (OC), microbial biomass, soil respiration, mineralisable N, and enzyme activities [19,20]. Keeley and Quin [17] reported a study of the effects of over 80 years of application of a meatworks effluent to a stony silt loam soil in Canterbury, New Zealand. In respect to the non irrigated control, the study showed considerable increases in soil potassium (1.4 vs. 0.4 cmolc kg^{-1}), organic carbon (4.45 vs. 3.88% C), pH (6.4 vs. 6.1) and base saturation (87 vs. 66%) can occur with effluent irrigation. McCarthy [21] reported significant improvement in wine grapevine vegetative growth, yield and total potassium concentration of wine after irrigation with sewage effluents.

Land application of wastewaters can increase the levels of soluble and exchangeable forms of potassium in soil expressed as potassium exchange percentage (EPP) more rapidly than with conventional inorganic fertilizers. Most of the potassium in wastewater is immediately available [22]. Because of the equilibrium between the different potassium forms in soil it is possible that application of high potassium wastewaters, (500–20,000 mg L^{-1}) can cause a consistent and rapid increase of potassium in solution. This, localized increase of potassium concentration in soil will cause the re-entering of potassium in the wedge-zones of hydrated micas, of vermiculite and illite.

A study by Gallardo-Lara et al. [23] indicated that disposal of OMWW induced a significant increase in the potential potassium reserve in soil (potassium firmly bound in minerals). The study revealed that OMWW applied to ryegrass increased availability and soil extractability of potassium, surpassing that of mineral potassium fertilizer [23]. Wen et al. [24] reported that potassium applied to crops of lettuce and snap beans was as equally available as inorganic fertilizer. Similarly, Gallardo-Lara et al. [25] found that the application of OMWW significantly increased exchangeable potassium in the soil but the effect of wastewater was less than that of inorganic fertilizer. They found that the treatment significantly increased water-soluble and exchangeable potassium compared to a control treatment with potassium fertilizer. In contrast, the increases in potassium firmly bound in minerals and total potassium were not significant. Similarly, another study using olive mill wastewater on ryegrass [25] revealed a lower increase of the amount of exchangeable potassium with respect to soil treated with mineral potassium fertilizer. Differences reported in the fertilizer potential of the wastewaters are mainly derived from different initial quantities of OMWW and fertilizer applied, different environmental conditions and composition and quantities of soil clay minerals.

Wastewater application not only increases these forms of potassium in solution, but also the organic matter of the soil and in turn, its cation exchange capacity (CEC). Wastewaters have different concentrations of the major cations (K, Ca, Mg, Na) that can affect the soil base saturation. The sodium adsorption ratio (SAR) and potassium adsorption ratio (PAR) are used to express the relationships between sodium content and Ca plus Mg contents and relationships between K content and Ca plus Mg contents, respectively [26]. When disposing wastewater onto soil competitive adsorption of cations on soil exchange sites occur, involving multiple species present in the wastewater, initially resident on exchange sites (mineral and organic), in the soil solution, or as salts in very dry soil [27]. With dilution by the infiltrating wastewater, soil exchange sites generally prefer counter ions of highest valence, like Ca and Mg, whereas an increase in total solution concentration in the soil solution tends to enhance adsorption of monovalent species, like Na and K [28]. Several examples are reported regarding the increase of soil base saturation. Bernal et al. [29] reported the change in soil exchangeable potassium after 8 months of application of pig slurry (K between 1100 and 3300 mg L^{-1}) at a range of rates from 200 to 1000 m^3 ha^{-1} year^{-1} on two calcareous soil (Typical Calciorthids) with two successive crops of pepper and tomatoes in Spain, (Table 4). Increases of exchangeable potassium in the soil after the first crop become significant with slurry application of 500 m^3 ha^{-1} year^{-1}. The soil with the higher clay content (illite) retained potassium in the exchangeable form to a much greater extent than the soil with a low clay content. Smiles and Smith [30] reported on an irrigation study with piggery effluents in south-eastern Australia. The effluent had pH values of 7.5–8, K levels of 370–650 mg L^{-1}, Na concentrations of 140–220 mg L^{-1}, PAR values of 10.2–14.2 and SAR values of 6.1–8.6. The results showed that electrical conductivity (EC), exchangeable potassium ratios and PAR values in the soils that had been irrigated with the wastewater were greater than their non-irrigated partners. Some studies [17,31] reported a significant increase in base saturation and exchangeable potassium with application of fellmongery and wool scour effluent. Kumar and Kookana [19] reported that long term application of winery wastewater with a range of salinity of 0.09–0.3 S m^{-1} and concentrations of K and Na of about 400 mg L^{-1} in vineyards, pastures and woodlots resulted in a build-up of available potassium levels to 1,400 mg kg^{-1}.

Potassium exchange reactions with Ca, Mg or Na on clay minerals and soils have been studied extensively. Some studies have shown that Ca or Mg ions are selectively adsorbed relative to potassium [32], while other studies reported soil preference for K over Ca, Mg, and Na [33]. Certain minerals have a specific preference for potassium such as vermiculite. Soil sorption of K can be greater

Table 4
Evolution of K (cmol$_+$) kg^{-1} forms 8 months after application of pig slurry to calcareous soils [29]

Rates (m^3 ha^{-1} year^{-1})	Soil 1					Soil 2				
	Pepper		Tomato		Tot	Pepper		Tomato		Tot
	Add	Exch	Add	Exch		Add	Exch	Add	Exch	
0	0.00	0.13	0.00	0.11	0.00	0.00	0.52	0.00	0.33	0.00
200	0.30	0.15	0.28	0.16	0.58	0.26	0.48	0.26	0.40	0.52
400	0.61	0.18	0.56	0.27	1.17	0.54	0.53	0.49	0.49	1.03
500	0.74	0.24	0.69	0.27	1.43	0.64	0.59	0.59	0.67	1.23
600	0.92	0.35	0.85	0.56	1.77	0.79	0.61	0.72	0.53	1.52
800	1.20	1.10	1.10	0.55	2.30	1.02	0.56	0.95	0.59	1.97
1000	1.51	0.33	1.38	0.88	2.89	1.31	0.66	1.20	0.80	2.51

than for Ca and Na. For example, Levy and Torrento [22] reported that sorption of K was about 10 times greater than that of Na. This is mainly related to the mineral composition, salinity and moisture content of the soil. Some minerals such as illite and vermiculite can selectively adsorb potassium over other ions with potassium held between the platelets of ‘shrink-swell’ clay minerals.

The effect of high concentrations of potassium on the selectivity of exchange sites for potassium in relation to Mg, Ca and Na is not clear. Elprince et al. [34] suggested that it would be possible to predict cation exchange in a ternary system from binary exchange data. Chu and Sposito [35], on the other hand, concluded that the behaviour of a ternary exchange system cannot be predicted from data on a binary exchange system alone. Levi and Feigenbaum [33] studied ternary (K–Na–Ca) exchange in two Israeli calcareous montmorillonitic soils with low organic matter content, using SAR and PAR solutions in the range of 1–15. They found that binary selectivity coefficients could be used for a multicationic system. The authors concentrated on the effect of Na on the selectivity of the soil for potassium, the inverse effect of potassium on the selectivity coefficients for Na was not investigated.

Robbins [27] showed that a decrease in the Na:K ratio from 20:1 to 1:1 in the soil solution resulted in a dramatic decrease in the soil’s preference for Na. A wide range of SAR values was used in this study and the decreased preference for Na could clearly be observed only at SAR levels >30 [27]. Although these results seem to indicate that high potassium waters could be used to alleviate high Na soils, one should be aware that potassium may also have a detrimental effect on soil structural stability [32,36].

Potassium availability is also strongly affected by the pH of the wastewater as well as by the pH of the receiving soil. Normally, potassium availability is sustained for most plants in neutral or slightly acidic soils. Some liquid wastes from industrial sources, such as in meat or dairy processing are characterized by high pH, 10–12 in meat [17] and milk factories [37]. Keeley and Quin [17] have reported significant increases in soil pH following the application of fellmonger effluent and milk factory wastewater. Campbell et al. [31] reported increases in soil pH following the application of wool scour effluent to a Waimakariri sandy loam in Canterbury, New Zealand. Falkiner and Polglase [38] also found increases in pH of forest soils following irrigation with sewage effluent.

Other wastewater such as winery effluents can have acidic pH values, sometimes close to pH 4. Irrigation with wastewaters can therefore either decrease or increase soil pH, dependent on the wastewater pH, the initial soil pH and the pH buffering capacity of the soil.

4. Soil physical properties

The effect of wastewater application on soil structure depends on the composition of the water, the exchange complex, the ionic strength of the soil solution and the clay mineralogy, within the soil [39–42].

Only limited research data exist on the effects of potassium on soil structure stability [26,43–45].

The literature shows a broad spectrum of possibilities for potassium’s effect on infiltration, ranging from being similar to sodium (negative effect) to being similar to calcium (positive effect). However, it seems that the overall effects of increasing exchangeable potassium and Na can negatively impact on soil hydraulic conductivities and infiltration rates. Quirck and Schofield [45] reported that exchangeable K and Na have a similar deleterious effect on hydraulic conductivity. Similarly, Rengasamy [46] found modest differences in flocculation potential between Na and K. Other researchers have reported that this is not the case, and the effect of exchangeable potassium, while not as detrimental as Na addition, is also not clearly beneficial as is Ca addition [43]. Chen et al. [44] showed that an exchangeable potassium percentage (EPP) of 20–30 improved the hydraulic conductivity of two Israeli soils, but had a negative effect on a third. Thus it seems that the research data is inconclusive, showing a broad spectrum of possibilities for the effect of potassium on hydraulic conductivity, ranging from being similar to that of Na to being similar to that of Ca. These conflicting results have been in part explained by differences in clay mineralogy. In the studies where potassium was found to be similar to Na in effect, or intermediate in effect between sodium and calcium, the soils were mainly kaolinitic or illitic. When the soils contained mainly smectites with high charge densities the effect of potassium on the hydraulic conductivity was comparable to that of calcium [39].

There is a general presumption that Australian soils have few structural stability problems associated with potassium and that Na is the central concern [32]. The review of Sumner and Naidu [40], which makes no reference to potassium in its index despite its focus on soil physical properties, exemplifies this view. Similarly, Rengasamy [46] suggests ways to incorporate effects of potassium in his assessment of clay dispersion, but implies that it generally may be ignored when he observes, with the exception of the soils treated with effluents from piggeries, wool scour and wineries, that soluble potassium is constant and negligible. It is well known that Na can have a negative effect on soil structure and reduce water infiltration rates.

Shainberg et al. [43] found that the effect of SAR on dispersion depended on the electrolyte concentration. Dispersion would not normally occur during wastewater irrigation so long as the electrical conductivity of the wastewater remained above the critical coagulation value. When both the electrolyte and SAR were relatively high soil structure was not affected by a high SAR, whereas low electrolyte concentrations enhanced clay dispersion. This has an important practical implication. Many of the wastewaters that are high in K or Na also have a high level of overall salinity and this will mitigate the impact of K and of Na on aggregate stability and hydraulic conductivity.

Some studies report that potassium in wastewater reduced water infiltration rates.

Peacock [47] determined the effect of potassium added to irrigation water at a concentration of 120 mg L^{-1}, on the rate of water infiltration under drip irrigation in a sandy loam soil. The potassium significantly reduced infiltration rates compared to the untreated control, and the drop in the infiltration rate occurred within 2 weeks of the first application of potassium. After 4 weeks the infiltration rate dropped to less than one-fifth the infiltration of the untreated control.

Distillery effluent (DE) contains a significant quantity of salt (~2.5 dS m^{-1}) and potassium concentrations of up to 15,000 mg L^{-1}. Information on the effect of application of DE on physical properties of soil is limited. Pathak et al. [48] reported an increase in the saturated hydraulic conductivity and decrease in bulk density of the soil, but Singh and Bahadur [49] reported a decrease in infiltration rate of an Inceptisol. Pathak et al. [48] found that application of DE improved the water retention characteristics of the soil. Hati et al. [50] studied the effects of disposing DE on a vertisol and found an overall significant improvement in the physical properties. Land application of wastewaters with high pH as in meat and dairy processing is likely to dissolve soil organic carbon [51], which in turn may lead to the development of soil physical problems.

5. Leaching of potassium

The potential for accumulation of potassium in soil from wastewater disposal is high since the element has a low leachability. Potassium ions not adsorbed by plants are adsorbed by the soil particles thus minimising the risk of potassium leaching. Almost all exchangeable and non-exchangeable soil sites would have to be potassium-saturated before there is a serious risk of leaching [52]. Studies on cation migration in water draining through the soil profile showed that potassium is not depleted relative to Na because potassium is liberated with greater difficulty from minerals and exhibits a stronger tendency to be retained in solid weathering products [53]. Disposal of high K wastewater on soil with a low content of selective adsorbing minerals like vermiculite and illite will increase risk of leaching as well in coarse sandy soil following saturation of the colloidal exchange sites [54].

The literature indicates several cases of potassium leaching after wastewater land disposal [12,52]. Phillips et al. [13] reported that multiple surface applications of piggery wastewaters caused significant amounts of potassium, up to 93% of total applied, to leach through the soil to depths of >50 cm. Leaching studies in organic crop rotation experiments showed that the average potassium leaching (to below 0.8–1 m depth) varied from 1 kg ha^{-1} on a loamy soil (24% clay) to 46 kg ka^{-1} on a coarse sandy soil (5% clay) [55]. Luo et al. [56] studied the effects of the application of meat processing effluents and observed that leaching losses of potassium increased significantly.

The level of potassium in groundwater is normally low, its presence at elevated levels down gradient of processing facilities can be indicative of impact from land application of wastewater. Elevated levels have been seen down gradient from the disposal of wastewater from piggeries and wineries [19,30]. Potassium in wastewater is not known to cause adverse health effects [57]. Most of the drinking water regulations do not establish a threshold concentration for potassium. However, a maximum admissible concentration value for potassium in water for human consumption of 12 mg L^{-1} was established by the European community [58]. This administrative threshold value has been criticised because it has no toxicological or physiological justification and is unnecessarily low from nutritional and health aspects [59].

Table 5
Typical K uptake (DM) by some crops [73–76]

Crop	Yield (t ha^{-1})	Uptake (K) (kg ha^{-1})
Lucerne (*Medicago sativa*)	25	554
Clover grass grass mixtures (*Trifolium* spp)	15	332
Coastal Bermuda grass (*Cynodon dactylon*)	25	443
Coffee (*Coffea arabica*)	2	147
Maize (*Zea mays*)	18	237
Cotton (*Gossypium hirsutum*)	2	193
Grain sorghum (*Sorghum bicolour*)	13	245
Oil palm (*Elaeis guinneis*)	79	245
Peanuts (*Arachis hypogea*)	5	193
Soybeans (*Glycine max*)	3	189
Wheat (*Triticum aestivum*)	2	149
Banana (*M. sapientum*)	77	1,188
Grape (*Vitis vinifera*)	15	150

6. Wastewater disposal and potassium uptake by plants

Potassium in wastewater is normally in mineral form that is available for plant uptake [60]. Therefore, the concentration of potassium in the wastewater, volume applied and reactions in the soil determine the quantity of potassium available to meet crop demand. A particular crop's suitability for use with high potassium wastewater can be assessed by evaluating plant factors including potassium uptake and changes in yield. The potassium utilized by several crops is shown in Table 5. Some plants such as banana (*Musa sapientum*) and lucerne (*Medicago sativa*) have an extraordinary capability to accumulate potassium (up to ~1200 kg ha^{-1}) [10]. In planning for the effective use of wastewaters with high potassium levels it is important to know not only the overall nutrient uptake, but also the plant removal efficiency. Removal of potassium in harvestable products is shown in Table 6. Tomatoes have one of the highest potassium removal rates. Mengel et al. [60] reported an overall uptake of 617 kg ha^{-1} and a fruit removal of 170 kg ha^{-1}. As a comparison, total potassium uptake of wheat is about 149 kg ha^{-1} and potassium removal in grain is 40 kg ha^{-1}.

Most of the studies concerned with the effects of using high potassium wastewaters have assessed grasses, as they are widely recognized to possess a high potassium removal potential [61]. In a review of potassium concentrations in temperate grasslands, Whitehead [4] reported potassium concentration of 25 g kg^{-1} as typical of grass, with different species in the range 15–35 g kg^{-1} (ryegrass and white clover). Grass and legume herbage from Pennsylvania and New York State (>9000 samples) had mean potassium concentrations of 21 g kg^{-1} (range 20–49), timothy samples from Finland (>2000 samples) 24 g kg^{-1} (range 8.0–43) and grass herbage from England and Wales (>1400 samples) 26 g kg^{-1} [4]. The concentration ranges reported above show that grass potassium concentrations are often well above the conventional standard

Table 6
Potassium removal rates for various crops [73,75,4,66]

Crop	Yield (t ha^{-1})	Removal (K) (kg ha^{-1})
Orange (*Citrus aurantium*)	40	79
Tomato (*Tomato esculentum*)	60	170
Banana (*M. sapientum*)	50	774
Spinach (*Spinacia oleracea*)	25	142
Potato (*Solanum tuberosum*)	40	166
Wheat (*T. aestivum*)	4.0	40
Soybean (*G. max*)	3.5	43
Maize (*Z. mays*)	9.0	162

Table 7
Potassium concentration (g kg^{-1} dry matter) of plant parts of annual ryegrass, 3 cereals and 12 legumes [68,70,72,87,88]

	Stems	Leaves (g kg^{-1})	Flowers	Roots
Annual ryegrass	9.0	14.7	14.6	1.6
Cereals				
Oat (*Avena sativa*)	16.3	13.0	15.3	6.1
Rye (*Secale cereale*)	13.6	9.1	13.1	4.0
Wheat (*T. aestivum*)	9.6	12.1	11.4	4.0
Legumes				
Austrian winter pea (*Pisum sativum*)	15.7	15.9	21.3	14.6
Arrow leaf clover (*Trifolium vesiculosum*)	6.2	7.0	12.3	10.6
Ball clover (*Trifolium nigrescens*)	17.1	12.0	15.8	7.1
Caley pea (*Lathyrus hirsutus*)	9,4	8.6	12.3	4.4
Crimson clover (*Trifolium incarnatum*)	13.1	12.4	15.8	8.0
Hairy vetch (*Vicia villosa*)	16.9	19.2	26.9	11.4
Persian clover (*Trifolium resupinatum*)	12.6	6.4	9.2	9.9
Red clover (*Trifolium pratense*)	9.1	18.9	14.6	9.3
Rose clover (*Trifolium hirtum*)	11.7	10.9	10.7	8.4
Subterranean clover (*Trifolium subterraneum*)	16.8	19.0	20.8	5.4
White clover (*Trifolium repens*)	8.6	18.1	nd	5.9

values (25–35 g kg^{-1}) used in mass balance calculations [62]. Turf grass is relatively resistant to salinity and the high shoot and root density of turf grasses can allow large volumes of wastewater to be applied. The salinity tolerance of turf was studied by Harivandi et al. [63] who stated that as salinity levels increased there is a concomitant increase in the osmotic stress placed upon the plant, with an increase in the salt ion accumulation in the turf tissue. This would result in a decrease in turf growth (particularly in the shoots), an increased root–shoot ratio, and a potential for nutrient imbalances with a decrease in tissue levels of potassium. The same authors studied the effects of the presence of high concentrations of potassium, ~1200 mg L^{-1}, in wastewater on ion uptake and growth of several turf grass species. They found that wastewater irrigation did not significantly increase potassium uptake and the plants did not manifest any symptoms of stress. The study suggested that turf grass species are relatively tolerant to salt concentrations, and under appropriate management, wastewater can be used for turf grass irrigation with minimal environmental impact. Another study [64] found that long term wastewater application on tall fescue pastures increased plant potassium concentration.

In forages, potassium accumulates at very different concentrations. Pederson et al. [65] reported that potassium concentrations were higher in stems and leaves of annual ryegrass than in similar portions of the legumes Ball clover (*Trifolium glomeratum*) and Austrian winter pea (*Pisum sativum*). The greatest difference in potassium concentration between annual ryegrass and the legumes was observed in the roots. Eleven of 12 legumes species had greater root potassium concentrations than annual ryegrass (Table 7). Oats (*Avena sativa*) had greater potassium concentration in stems and roots than annual ryegrass. From the perspective of appropriate wastewater management in the short term, the accumulation of potassium in roots can be useful. While leaves can be harvested or grazed, roots remain *in situ* and are effective in potassium immobilization, potentially reducing losses by leaching.

Allhands et al. [66] studied the potassium uptake of warm-season Bermuda grass (*Cynodon dactylon*) after irrigation with municipal wastewaters. A linear increase in potassium plant uptake with harvest interval was observed relative to the control for all the warm-season Bermuda grasses studied. For a seasonal loading rate of 97 kg K ha^{-1}, Bermuda grass production was estimated as 7.43 Mg ha^{-1} dry matter yield and plant uptake of 53 kg K ha^{-1}. Corresponding values for winter rye (*Secale cereale*) were 4.25 Mg ha^{-1} and 66 kg K ha^{-1}. Gamroth and Moore [67] conducted a study on the uptake of K in perennial grasses fertilized with dairy manure. The author tested 11 ryegrasses, 4 orchard-grasses, 5 fescues, 1 festuolium, and 1 prairie grass variety. Plant tissue potassium values were fairly consistent throughout the season and potassium removal ranged from 484 kg ha^{-1} (*Elgon ryegrass*) to 708 kg ha^{-1} (*Bronsyn ryegrass*). A consistent accumulation of potassium was also reported by Palazzo [68] who studied the uptake of potassium by orchard grass irrigated with municipal waste water with peak potassium uptake during the first harvest.

Wu et al. [69] present the effects of high potassium irrigation waters on potassium uptake of cleopatra (*Canna cleopatra*), dwarf yellow daylily (*Hemerocallis minor*), *Japanese water iris* (*Iris ensata*) and *garlic* (*Allium sativum*). Potassium uptake was significantly different between the plant species, but was not significantly different between wastewater irrigation treatments. They concluded that on these ornamental plants the high potassium in wastewater did not seem to create any mineral concentration stress or growth reduction.

Correlation studies have revealed a positive correlation between plant and soil potassium concentrations, as well as between plant and wastewater potassium levels [70]. These authors investigated the nutritional status of different orchards irrigated with domestic wastewater in Pakistan. A linear relationship between the level of potassium in the effluents and potassium accumulation in the plants was found. Loquat, peach and plum orchards were deficient in potassium, whilst peach had adequate potassium and the apricot orchard had high potassium concentration. The study showed irrigation of wastewater can replace a portion of synthetic fertilizer.

Studies have also been conducted on grape vineyards. Paranichianakis et al. [71] studied the effect of reclaimed wastewater on grapevines. The concentrations of potassium and N in the wastewater were 21–28 mg L^{-1} and 10–20 mg L^{-1}, respectively, the level of potassium in the control fresh water was 2.5–3.0 mg L^{-1}. They found that the irrigation with both waters was sufficient to cover vine potassium requirements, while supplemental N fertilization was required. Significant differences in the uptake of potassium between rootstocks were also found. Pinamonti [72] studied the potassium uptake in a vineyard irrigated with sewage effluent and found that potassium removal was correlated with the rate of addition of the effluent.

7. Conclusions and future research needs

In preparing this review, it has become apparent that research into the fate of potassium in the soil–plant system under wastewater application is limited. Irrigation with high potassium effluent has been shown to help sustain the overall fertility in soils. In general the wastewater constitutes a fertilizing mineral and organic matter potential and hence the potassium in wastewater can behave differently to fertilizer potassium. Disposal of high potassium wastewater in soil with a low content of selective adsorbing minerals will create very high concentrations of potassium in solution with potential effects on soil structure and potassium mobility. However, the effect of disposing high potassium effluents on soil structure is still not clear and more research is needed.

When using high potassium wastewater, appropriate management strategies have to be developed, which minimize leaching losses from the crop-root-zone (by optimization of wastewater application) and maximizing nutrient removal (through reaction with soil colloids and synchronizing wastewater applications with crop uptake). Other practices like wetting and drying could increase potassium-fixation in silicate minerals (i.e., vermiculite) therefore reducing potential leaching. For sustainable disposal of wastewaters of plant tolerance and uptake of potassium must also be known.

Further research needs also to focus on the effect of the K:Na ratio in the wastewaters and its effect on potassium availability and leaching in soil and potential increased plant tolerance to salinity.

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