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Forest fertilization: Trends in knowledge and practice compared to agriculture

Philip J Smethurst

Abstract Plantation forestry continues to intensify and grow in area, with a concomitant increase in fertilizer demand. Virtually no fertilizer is used on non-plantation forest systems. The scale of fertilizer use per ha per year in a small proportion of plantation systems is now similar to some agricultural production systems, but the total area of plantation forestry remains only a few percent of that used for agriculture. Hence, in a global context, forestry is a minor user of fertilizers. In relation to the knowledge base for fertilizer management, forestry and agriculture have similar practical questions that drive research, i.e. nutritional diagnosis and the development of fertilizer prescriptions that optimize production, environmental and economic goals. Much of this research is soil-climate-species-management specific. During the past few decades, solution culture methods were developed that maintain stable internal nutrient concentrations, which were essential for improving our understanding of nutrient-growth relationships. The development of plant production models that include the mechanistic simulation of nutrient supply and uptake are at an early stage of development. Plantation forestry and agriculture lack a mechanistic basis for evaluating base cation availability that accounts for Al-pH-root interactions. Further developments in this field could assist in rationalizing the use of lime. There is a lack of resources available in plantation forestry, and probably also in agriculture in some countries, to develop and refine calibrations of traditional types of soil and foliar analyses. Further testing of soil solution approaches is warranted. Further research on resource use efficiency, wood quality, rhizosphere relations, and mixed-species systems in relation to fertilization is also warranted.

Keywords N-fixation • plantations • nutrients • soil testing • lime • rhizosphere

Introduction

Fertilizer use in forestry is almost entirely restricted to plantations, of which there

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were 140 Mha world-wide in 2005 when this land use was increasing by 2.8 Mha annually (FAO 2006). The plantation area is likely to continue to expand, and almost all plantations receive fertilizer at some stage of their development. Hence, an increasing area of plantations leads to an increase in the demand for fertilizers in forestry. Another factor driving increased fertilizer usage in forestry is the level of intensification of management, with the objective of increasing the average rate of wood production per unit of land. Intensification reduces the duration of the crop cycle and increases the frequency of harvesting, and, because younger trees have higher concentrations of nutrients, it increases the average rate of nutrient export.

Until about three decades ago forest plantations had a rotation cycle of at least two decades, which was many times longer than most agricultural crops, but increasing demand globally has intensified management and led to rotation lengths of 4- to 7-years in some countries for growing several *Eucalyptus* and *Acacia* species. Demand for wood for traditional uses (paper, sawn timber, veneers, charcoal and firewood) drove this intensification, and short-rotation tree crops are emerging as a possible option for producing bioenergy (Gopalakrishnan et al. 2009). Most perennial horticultural crops have much longer rotations than these short-rotation forest plantations. Therefore, in relation to annual fertilizer application requirements, many forest plantations can be considered broadly similar to annual or perennial agricultural crops. However, Asia and South America, where the shortest-rotation forest plantations are grown, together account for only 24% of industrial roundwood production globally (FAO 2005). Most roundwood is still produced in much longer rotations in Europe, North America and Oceania from natural forests and plantations.

Forest nutrition research can be considered to have begun with the first detailed publications by Ebermayer in 1876 and 1882 in Germany, when it was noted that the periodic removal of the forest litter layer for use as animal bedding led to unhealthy forests, and that this effect was nutritionally mediated (cited by Attiwill and Leeper 1987, Rennie 1955 and Tamm 1995). Since Ebermayer, forest nutrition research has bolstered general knowledge of soil-plant nutrient relations in synergy with developments in agriculture and other domains of plant nutrition. Agricultural research with artificial fertilizers began around 1842 when Lawes and Gilbert took out a patent on the production of superphosphate, and in the same year Lawes published the effects on cabbage growth of applying different forms of inorganic nitrogen fertilizers (Johnston 1994). Only a few years later in 1847, inorganic fertilizer experiments on forest soils commenced in France (Baule and Fricker 1970, cited by Pritchett 1979). However, forest fertilization commenced operationally for many plantation types only in the 1950s, after the development of reasonably sound scientific principles (Ballard 1984). The use of fertilizer in forestry increased during the 1960s and 1970s as the economic value of fertilization became apparent; fertilizing to maximize tree growth rate became a priority (Cromer et al. 1977; Schönau and Herbert 1989). As the need developed to refine the management of forest fertilization, which was mainly in a plantation context, forestry began to contribute generally to the science of fertilization.

The objective of this review is to provide an overview of fertilizer usage in forestry internationally and the history of forest nutrition research, and describe developments in specific aspects of the knowledge base of forest fertilization that have implications for other cropping systems. I conclude by identifying major knowledge gaps and likely future trends in the research and practice of forest fertilization.

Goals of fertilization

In agriculture, fertilizers can be used to increase vegetative growth and total biomass production, e.g. for root-crops and pastures, but most fertilizers are used to increase reproductive growth for food production, e.g. cereals, oilseeds, and horticulture. In addition to maximizing yields, fertilizers are managed in many instances to optimize product quality, which is achieved by synchronizing the rates and timing of fertilization with the stage of growth. In contrast, the main goal of fertilization in forestry is to increase biomass production for wood volume and weight (which is the main context of other sections of this review) whilst avoiding serious deteriorations in wood quality. On a small scale, fertilizers are also used in forestry to manage seed production (Williams et al. 2003).

Where it has been of interest, wood quality in relation to fertilization has mainly been assessed for pulp and paper purposes. The principle qualities of interest are wood density, fibre diameter and length, microfibril angle, cell wall thickness, and contents of lignin, cellulose and extractives. The high cost of assessing these attributes has hindered progress, but the use of NIR analyses has recently reduced the cost and increased research in this area. In relation to eucalypts, fertilizer generally either increases or has no effect on wood quality, but it increases the nutrient content of wood and hence nutrient export from sites (Raymond 1998). In conifers, fertilization that increases growth rates also tends to decrease wood density, but overall there is usually an increase in the total value of wood for sawn timber or pulpwood (Antony et al. 2009; Cao et al. 2008; Downes et al. 2002, Nyakuengama et al. 2002; Zobel 1992). Overuse of fertilizers in forestry can result in trees with multiple or contorted stems that greatly reduces the value of the tree for either pulpwood or sawn timber purpose (Turnbull et al. 1994).

Fertilizer use in forestry

Forest plantations are widespread around the globe, with large areas in suitable parts of Asia, the Americas, and Europe, and much smaller areas in Africa and Oceania (FAO 2006). World-wide, forest plantations grown for wood products occupy about 3% of the total land area used for food and fibre production. The same percentage applies to Australia, where the low percentage of land used for plantations compared to agriculture, combined with low average annual rates of fertilizer usage per ha, results in plantations accounting for only 0.12% of N and 0.24% of P fertilizer usage (May et al. 2009b).

While the proportion of total fertilizer usage in plantations, and the average *annual* rates of application are low, *per application* the amounts and types of fertilizers are broadly similar to those in agriculture (Table 1). There is far less frequent use of fertilizers in forest plantations, where applications during the first year are common but later applications range from annually to never. The forms of fertilizer used in forestry mirror those used in agriculture, but some forestry-specific blends are available.

Like other cropping systems, the emphasis of most forest fertilization research has been on diagnosis of nutrient limitations in specific contexts (i.e. combinations of soils, climate, species and management) using soil and plant analyses, and the refinement of fertilizer rate, timing, form and placement options (Fox et al. 2007; Gonçalves and Barros 1999; Smethurst et al. 2004a). Fertilizer placement in a plantation considers uptake efficiency and the relative value of placement options. Planting densities are commonly 1000-2000 trees per ha, which means plants are several meters apart. Young tree seedlings have only small root systems. Therefore, applications around planting time are usually localized in concentrated spots or bands 10-50 cm from the planting position on or below the soil surface, or over small areas close to the plant (Smethurst and Wang 1998). As the root system develops, the zone of application usually increases in area until totally broadcasting the fertilizer becomes efficient (Attiwill and Adams 1996; Smethurst et al. 2004a), which in most countries is the cheapest and preferred way to apply fertilizer. Modern navigational methods aid the selection and recording of ground or flight paths for fertilizer application, which in-turn improves the uniformity of application, and improves the ability of pilots to avoid buffers and other areas that are not to be fertilized (e.g. McBroom et al. 2008).

Examples of Forest Fertilization

Slow-grown conifers Some plantation conifers in Europe are grown in rotations of several decades (e.g. 92 years in central Sweden) and fertilized at planting with multi-nutrient mixes (Evers 1991). Thereafter N fertilizers are applied at various intensities up to 150 kg N ha^{-1} every 5 years, but more commonly less frequently or never (Eriksson et al. 2007). When these plantations are fertilized, it is commonly by broadcasting calcium ammonium nitrate or NPK mixtures.

Medium-growth-rate conifers Coniferous plantations in Australia and the south-eastern USA grown in 15- to 30-year rotations are commonly fertilized at establishment with NPK mixtures applied close to the planting position, and

Table 1 Summary of fertilizer use in selected plantation forest and agricultural systems.

Crop, Country	Nitrogen			Phosphorus			Ages or frequency applied	Other nutrients commonly required
	Average rate applied (kg ha^{-1} year^{-1})	Common high rate (kg ha^{-1} application^{-1})	Common forms*	Average rate applied (kg ha^{-1} year^{-1})	Common high rate (kg ha^{-1} application^{-1})	Common forms[1] (years)		
Forest plantations								
Eucalyptus, Brazil	7	20	U, AS, MAP, DAP	8	53	PR, MAP, DAP	Split 0-2 years	K, B
Pinus, USA	6	224	U, DAP	2	50	DAP, SP, PR	0, 2-22 years	B, K, Mg
Pinus, Australia	4	208	U, AS	2	112	DAP	0, 1-25 years	K, S, Cu, Zn, B
Eucalyptus, Australia	10	104	AS, U	4	54	DAP	0, 1-12 years	K, S, Cu, Zn
Agricultural systems, Australia								
Dairy	20	200	U	25	75	MAP, DAP, SP	1-4/year	K
Sugarcane	160	300	U	20	38	SP, DAP	1-2/year	K
Horticulture	100-800	8-64	U, DAP, MAP, KN	18-100	2-10	DAP, MAP	1-12/year or	K fertigation every 1-2 days
Cereals, oilseeds	30	200	U, AS	10	10	SP	1/year	K, S

Main sources: Barros and Novais (1996) Barros et al. (2004), Gonçalves et al. (2008), Albaugh et al. (2007), May et al. (2009b)

* U urea, AS ammonoium sulphate, MAP, mono-ammonium phosphate, DAP di-ammonium phosphate, PR phosphate rock, SP superphosphate including triple superphosphate, KN potassium nitrate

application rates are 10-50 kg ha^{-1} each of N and P (Fox et al. 2007; May et al. 2009b). Established stands receive nutrients at high rates of 208-324 kg N and 50-112 kg P ha^{-1} broadcast every 5-15 years.

High-growth-rate eucalypts Some eucalypt plantations in Brazil are grown on 6-year rotations that receive 2-3 applications of 20 kg N and 53 kg P ha^{-1} (mainly as monoammonium phosphate and diammonium phosphate) during the first 2 years, plus K and B (Barros et al. 2004; Gonçalves et al. 2008). Eucalypt rotations of about twice the length are used in Australia, with generally higher N and lower P rates than those in Brazil.

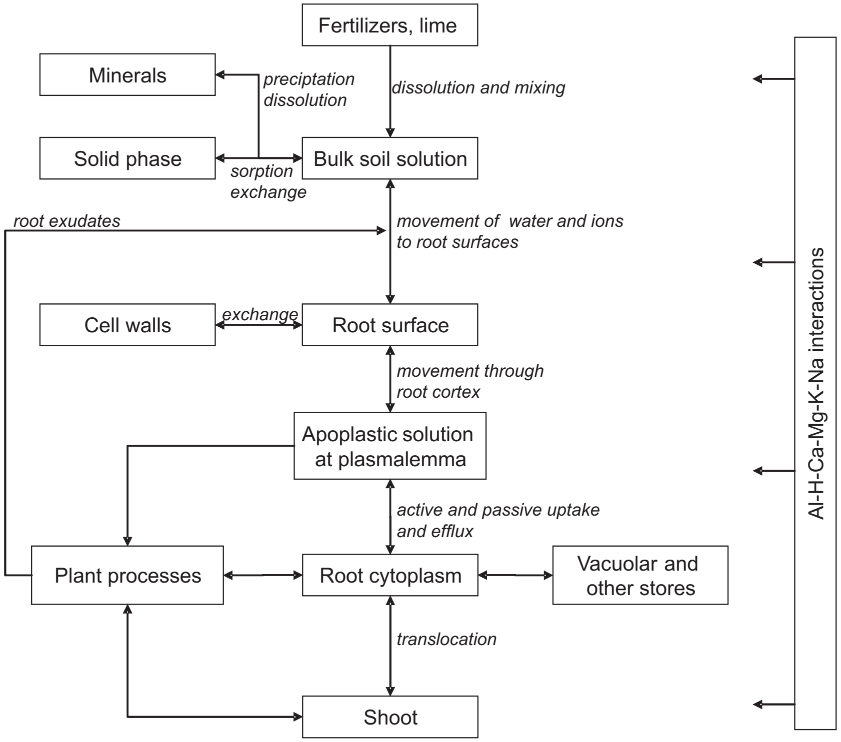
Liming

The use of lime (including dolomite) has increased in forestry during the past few decades in response to a perception that soil acidification and concomitant nutrient deficiencies threaten forest ecosystems. Liming of forests occurs predominantly in Central and Northern Europe (Kreutzer 1995; Meiwes et al. 2002). In Europe, soil acidification has accompanied the atmospheric deposition of nitrogen and sulphur generated from coal-fired power stations and from automobiles, i.e. the 'acid rain' effect. The realization of its potential consequences for forestry developed in the 1970s and 1980s, with the expectation that as a predisposing stress it would contribute to an increased incidence of toxicities and nutrient imbalances that would slow forest growth or in some cases lead to mortality (Hüttermann 1985; Matzner and Ulrich 1985). The accompanying critical load concept (Sverdrup and de Vries 1994) influenced many forest managers in Europe to commence or increase the use of lime (including dolomite). However, data on forest growth later indicated faster rather than slower growth of forests (Binkley and Högberg 1997), suggesting that the beneficial N- and S-fertilizer effects of atmospheric depositions outweighed any negative effects of acidification for several decades at least.

Liming can also have negative consequences associated with humus decay, nitrate concentrations in seepage water, mobilization of heavy metals, shallower root systems, boron deficiency and pathogens (Kreutzer 1995). Further, liming has had little effect on acidity in soil per se, because it is applied to established forests with a litter layer, and most of the chemical changes occur only in the litter layer. Changes in litter chemistry can result in higher rates of nitrification and increased rates of nitrate leaching at a catchment scale, and other adverse outcomes (Löfgren et al. 2009). Far more important to countering the effects of acid deposition than liming are the trends in electricity production during the past few decades that have reduced S deposition by 90% and N deposition by 50% in southern Sweden, for example (Löfgren et al. 2009).

Liming is also used routinely by some plantation forestry companies in Brazil to counter soil acidity, but its main purpose is to correct Ca and Mg deficiencies. This practice is not universal amongst plantation companies in that country, and experimental results indicate that liming to correct acidity is not warranted when planting with *Eucalyptus* or *Pinus* species, which are tolerant of acid soils (Gonçalves et al. 1997). What appears to be an unnecessary use of lime in Europe, and in some cases in Brazil, underscores the risks associated with acting on expected soil chemistry and plant growth effects without confirmation of the latter under normal field conditions. While some progress has been made in our understanding of the effects of forest liming, we particularly need to separate the effects of liming to alleviate the toxic effects of H and Al from those on nutrient availability at root membrane to stand scales. There is a larger knowledge base for some agricultural species, but in that domain too we still lack an adequate quantitative, mechanistic, understanding of the interactive effects of liming across a range of spatial and temporal scales. A schematic of the main pools and processes involved is presented in Fig. 1. A number of these aspects have been studied in

Fig. 1 Schematic diagram of the main soil-plant processes involved in Al-H-base cation availability responses to liming and fertilization.



detail for some soil-plant systems, but quantitative links have not been established for any plant-soil system. Until such understanding and quantification is available, we will have to rely on calibrated, empirical relations between fertilizer or lime applications and ecosystem responses.

Fertilizer use in agriculture

There is a very wide range of fertilizer practices used in agriculture due to the variety of natural and socio-economic conditions, crop requirements, nutrient forms and fertilizer availability. Examples are provided in Table 1 for some Australian agricultural systems, which show that relatively high annual rates are used in horticulture and sugarcane, and lower rates in cereals, oilseeds and dairy systems. These latter systems have rates about twice those in intensively managed forest plantations. Annual rates of fertilizer usage in Australian agriculture are within the large range reported for cropping and pastures in the UK (Chalmers 2001), vegetable crops in China (Chen et al. 2004), and also broad-acre and horticultural crops in various regions of the world (Crews and Peoples 2005).

Understanding Forest Nutrition and Growth

Nutrient cycling

Although fertilizer management in forest plantations is similar in principle and practice to many agricultural situations, differences in some aspects of nutrient cycling need to be considered. Prior to 1960, plant nutrition as a discipline had no particular emphasis on forests, but in the period 1960-1990 forest nutrition developed as a discipline of research by focusing on nutrient budgets and nutrient cycling in a variety of natural and managed forest systems (Smethurst 2004). Some of these systems had been fertilized, but not all. Comerford (2002) lists 16 key texts on forest soils published between 1983 and 2000 that document an increasing emphasis on nutritional management. To these can be added Bowen and Nambiar (1984), Nambiar and Brown (1997), and Gonçalves (2004) that specifically develop the topic in a plantation context.

As Comerford (2002) highlighted, there are several aspects of forest soils that are distinct from agricultural systems: time between harvests, nutrient cycling, erosion, topography, fertilization practices, irrigation, soil temperature, utilized soil depth, stoniness, remoteness from markets, and surface soil organic horizons. All of these differences impinge to some degree on fertilizer management, some of which are further explored here.

In trees, the annual requirement for nutrients for new growth is partially met by drawing on internal pools in older tissues rather than meeting nutrient demand entirely by uptake from soil. In this context, internal cycling includes the withdrawal of nutrients from aging or dying tissues and retranslocation of those nutrients to younger tissues. The importance of this process had been recognized by the 1970s (Wells and Jorgensen 1975), and it has been quantified in a number of forest systems since. In a 13-year-old, N-deficient *Pinus radiata* plantation, N fertilization led to a 45% increase in wood production and 350% increase in N retranslocation, showing increased reliance on retranslocation as growth rate increased (Fife and Nambiar 1997). Internal cycling of nutrients in three *Eucalyptus species, Acacia mearnsii* and *Pinus radiata* was studied between 12 and 22 months of age, during which 31-60% of N present in young, green foliage, 54-63% of P and 18-38% of K was retranslocated (Fife et al. 2008). Hence, such dependence on retranslocation probably exists among all or many forest plantation species. In contrast, annual agricultural crops depend almost entirely on uptake, during which sub-annual transfers of carbohydrates and nutrients are important for grain, fruit or tuber production.

Cycling of nutrients external to the plant is also prevalent in forests that have commenced above- or below-ground litter production, and it can account for a significant component of annual nutrient availability to tree roots. For example, tropical plantations of various species accumulate in litter 80-660 kg N and 4-20 kg P ha^{-1}, which is more than in many natural tropical forests (O'Connell and Sankaran 1997) and generally more than the average annual amounts of N and P accumulated in trees of tropical forest plantations (Gonçalves et al. 1997). Hence, retention of this material and harvesting residues between rotations is essential to reduce or alleviate the need for fertilizers during the early phase of the next crop (Nambiar 2008). Conversely, slow decomposition of litter in some systems, particularly in cold climates, immobilizes large pools of N and other nutrients (Tamm 1995). This build-up of nutrients in litter layers limits nutrient losses via leaching from these ecosystems, but it can also contribute to N deficiency in trees.

Links between nutrient cycling and catchment-scale outcomes were made early in forestry because some aspects of forestry practices were controversial, i.e. clearfelling and complete vegetation control using herbicides could lead to high nitrate concentrations in streams and ground water (Vitousek and Melillo 1979). Later studies have shown that N and P fertilizer in forestry leads to generally small and transient increases in N and P concentrations in stream water (Binkley et al. 1999). More recently, practices in agriculture have come under scrutiny in a nutrient context for potential adverse catchment scale and greenhouse gas outcomes (McDowell 2008). Agriculture generally, via fertilizer use, has caused a much larger perturbation of global nutrient cycles than forestry (May et al. 2009b). For example, by about 1990, global N fertilizer production, which is mainly used to produce food, and other anthropogenic influences had doubled the rate of N transfer from atmospheric to terrestrial pools compared to that which would otherwise have occurred due to natural processes (Vitousek et al. 1997). This proportion has probably increased substantially during the past decade.

Nutrient flux density and uptake kinetics

Developing a mechanistic understanding of nutrient uptake processes has led to the realization that nutrient uptake at the cell membrane level of roots and mycorrhizal hyphae was an active process mediated by enzymes. Together with nutrient supply phenomena in soils, supply and uptake could be mathematically modeled (Barber 1995; Tinker and Nye 2000). Between 1970 and 1991, the need to experimentally control plant growth rates and nutrient concentrations led to the development of hydroponic culture techniques that supplied all nutrients at non-limiting concentrations, except for one limiting nutrient (Asher and Blamey 1987; Asher and Cowie 1970; Ingestad 1971). Supply of the limiting nutrient (usually N) conformed to a schedule that directly led to control of the growth rate of the plant. Different exponential growth rates resulted in different but stable internal nutrient concentrations, which greatly assisted in the testing of various hypotheses of nutrient-growth relations in plants (Ericsson et al. 1995; Ingestad 1982).

However, Ingestad came to the conclusion that concentrations of nutrients in hydroponic and soil solutions and uptake kinetics of plant roots were unimportant for controlling plant growth rates (Ingestad 1982). Instead, the rate of nutrient replenishment was critical, which he and his coauthors termed the nutrient flux density approach. This method was also applied to several field experiments in forests around the world (Albaugh et al. 2007; Linder 1995) and was adopted by scientists working on nutrient-growth relations of other forestry, agricultural, and aquatic species (e.g. Groot et al. 2002; Hawkins et al. 2005; Macduff et al. 1993; Pintro et al. 2004; Raven 2001), because of the high level of control it offers over plant growth rates and internal nutrient concentrations.

The nutrient flux density approach presented a dilemma for some scientists working in the more common paradigm where concentrations in growth solutions and uptake kinetics were important (Macduff et al. 1993; Raven 2001). Sands and Smethurst (1995) subsequently demonstrated that these two approaches were not necessarily inconsistent by using uptake kinetic principles to model nutrient uptake and plant growth reported for one of Ingestad's experiments. A solution concentration of 50 mM inorganic N was required (via periodic or continuous replenishment) to produce a relative growth rate of 0.25. Building on the earlier work of Tinker and Nye (2000) and Barber (1995), nutrient supply and uptake theory has since been used to simulate nutrient uptake and growth of a eucalyptus plantation over several years with simultaneous potential limitations of N, P, light, water or temperature (Smethurst et al. 2004b).

CEC and base cations

Forest soils are generally more acidic and organic than soils used for agriculture. Experience with forest soils has questioned traditional views developed primarily in an agricultural context that use cation exchange capacity, base cation saturation and exchangeable cation concentrations as indicators of base cation availability (Ross et al. 2008). In such forest soils, the source of charge is mainly organic matter, and cation retention cannot be explained by simple exchange phenomena. Ross et al. (2008) argue four salient points that apply to acid soils across agriculture and forestry: (1) new measures of exchangeable Al and H are needed, (2) base saturation should be abandoned as a measure of base cation availability, (3) the paradigm that higher pH accompanies higher CEC does not hold, and (4) CEC should not be used to indirectly infer base cation availability. These observations will become more pertinent as agricultural and forestry soils acidify, which is a long-term trend globally, and as society is forced to use more acid soils to grow food and fibre.

In many parts of the world, salinity or sodicity adversely affects crop growth, and the problem is expanding. During recent decades, Na has been recognized as a functional nutrient for many agricultural plant species, and to some extent it can substitute for the functions of Ca, Mg and K (Subbarao et al. 2003). One implication is that increasing Na availability and uptake can reduce the need for these other base cations, and lower critical foliar concentrations can be used as a guide to fertilizer needs. However, few studies have demonstrated Na substitution of other bases under field conditions. A recent demonstration of this effect in a plantation forestry context comes from Brazil, where K depletion after several decades of eucalypt cropping led to substantial K deficiency (Almeida et al. 2009). Trees responded substantially to K fertilizer applications, and about 40% of that response was also achieved by Na fertilization alone.

Productivity modeling that includes nutrients

Agricultural crop productivity modeling that accounts for species-specific responses to light, water, temperature, and nitrogen was already well developed more than a decade ago (Hanks and Ritchie 1991; Keating et al. 2003), and has since expanded in sophistication and application. A similar model has been developed for forest plantations (Landsberg and Waring 1997), but it considers nutrients by using only a generic fertility factor, and it cannot account for fertilizer applications. A more mechanistic model has been developed that considers some silvicultural operations used in plantation forestry, including N fertilization (Battaglia et al. 2004), which was used to simulate N and P uptake and estimate growth limitation due to light, water, N and P (Smethurst et al. 2004b). Other forest productivity models have been developed that account for one or more nutrients (usually N), but none combine a high level of silvicultural flexibility with detailed nutrient dynamics and uptake by trees and weeds (Smethurst 2007). These process-based plantation forestry models also do not yet have the sophistication to account for all the options available for managing fertilizers, e.g. fertilizer forms and placement, but such developments are possible. Such detailed fertilizer management options can instead be compared using more empirical models or decision support systems based on experience and financial information (Fox et al. 2007; May et al. 2009a).

Nutrient use efficiency

Forest researchers have had an interest in nutrient use efficiency (NUE) for several decades. Based on litterfall as a surrogate for growth and net primary productivity (NPP), and litter N content as a surrogate for N supply, it was asserted that the more nutrient that was used the less was its NUE, i.e. biomass produced per unit of resource supply decreased with an increase in supply (Vitousek 1982). With actual measures of above-ground NPP (ANPP), Binkley et al. (2004) sought evidence that this was the case for the resources of light, water and nitrogen, and found that the few data available supported the opposite hypothesis, i.e. resource use efficiency increased with increasing resource capture. For example, across 14 *Eucalyptus* stands in Brazil, Stape et al. (2004) found that ANPP per unit of N uptake, increased about 30% with a 200% increase in N uptake, while litterfall per unit of N uptake and litterfall proportion of ANPP both decreased by about 50%, with a 300% increase in ANPP.

A key concept in agriculture is that resource use efficiency is based on product yield per unit of resource supply (e.g. Passioura 2004 for water). But for nutrients, the contribution of both fertilizer and soil sources needs to be considered, and resource capture needs to be separated from resource use within the plant. There are few data in agriculture or forestry that allow a full analysis of nutrient use efficiency, but instead product yield can be expressed per unit of external resource input (e.g. irrigation or fertilizer). This latter index has also been referred to as the partial factor productivity (PFP) of an applied nutrient (Dobermann 2007). Nutrient use efficiency can also be expressed as biomass or product yield per unit of nutrient taken up regardless of the nutrient source, which approximates to the inverse of the average concentration of a nutrient in a plant. It is important that such concepts are more fully understood by including below-ground productivity and measures of resource supply and resource capture, and that the implications for fertilizer practices are clarified.

Various fuel sources are used or considered for biofuel production, but these can have a very wide range of PFP values (Table 2). These data indicate that corn, cereals and pasture have very low PFP values (0.6-144) compared to some eucalypt plantations that had a low requirement for N fertilizer (2-14 kg), but similar to pine plantations that had a high N fertilizer requirement. Biofuel production requiring little or no fertilizer input would have a PFP value approaching infinity, e.g. in riparian plantings of trees and grasses that utilize nutrients in wastewater or polluted groundwater (Gopalakrishnan et al. 2009) or in parts of Europe and North America with high atmospheric deposition. As biofuel technologies develop to better cope with woody materials, it is expected that more of this feedstock will be used and thereby increase the N-use efficiency of biofuel production (Galloway et al. 2008), but it will be important to consider the N fertilizer requirement of the particular plantation system under consideration.

Table 2 Comparison of fertilizer nitrogen use efficiencies (NUE; PFP as defined by Dobermann 2007) of typical biomass produced from cereals, corn, and perennial pasture compared to stem wood from plantations that had relatively low (eucalypt) or high (pine) N fertilizer requirements. Corn and cereal biomasses were calculated using a harvest index (grain biomass to total biomass ratio) of 0.5 and 0.25 respectively (Donald and Hamblin 1976).

Crop	Fertilizer NUE (kg yield per kg N fertilizer)		Reference
	Minimum	Maximum	
Corn	1.2	2.6	Dobermann et al. 2002
Cereals	124	488	Dobermann 2007
Perennial pastures	32	144	Brouder et al. 2009
Pine plantations	16	44	Albaugh et al. 2004
Eucalypt plantations	2,222	13,545	Stape et al. 2004

Production systems with less fertilizer

There is a concern that the availability of inorganic N and P fertilizers will diminish as the surplus of supply over demand decreases (FAO 2008, Huang 2009) and as mineral reserves of P-containing rocks are depleted (Cordell et al. 2009). However, others argue that world reserves and resources for N and P appear adequate for at least the next two years (FAO 2008) and the foreseeable future (Fixen 2009). Under both scenarios, the price of fertilizers could increase relative to the cost of other farm inputs. Lack of availability, or economic pressures could therefore reduce the per ha use of these fertilizers and necessitate food and fibre production using lower nutrient input systems. This trend could in-turn expanded interest in the use of rhizosphere and mixed-species technologies that potentially add N and better utilise existing sources of soil N and P otherwise unavailable to crop plants. These technologies include enhanced P uptake by roots and mycorrhizae via organic acid and phosphatase production (Jones 1998, Richardson et al. 2009), symbiotic (Forrester et al. 2006) and non-symbiotic biological N-fixation, and improved plant root nutrient uptake kinetics (Bassirirad 2000, Raghothama 1999). There is scope for (1) using existing genotypes that can up-regulate these mechanisms, (2) selecting and breeding for new genotypes of plants and microbes, and (3) genetic engineering to induce or enhance these processes in important crop species (Schachtman and Shin 2007, Richardson et al. 2009). There will probably be a greater need for these developments in agriculture than in forestry, so important opportunities might develop for plantation forestry by being aware of such trends in agriculture. However, studies of forest and other non-agricultural crop species have contributed significantly to our current understanding of these processes, because of their importance in low-fertility, non-agricultural systems.

Mycorrhizae, fungal symbionts that infect the root system, act as a very fine extension of the root system with a high surface area to biomass ratio that enhances under some conditions nutrient and water uptake and the ability of a plant to cope with biotic and abiotic stresses. In return for these potential benefits, the plant supplies carbon to the fungus for growth and metabolism. Many of these functions are genetically mediated (Graham and Miller 2005). In relation to nutrient uptake, plants benefit most from the mycorrhizal symbiosis in terms of biomass growth and survival under conditions of low availability of poorly-mobile nutrients, e.g. P in highly P-limited natural and man-made ecosystems (Chen et al. 2008). In contrast, under high nutrient availability, infection and growth of mycorrhizae can be negligible, or the cost in terms of carbon can reduce plant growth where nutrient uptake is not enhanced by mycorrhizae. These principles have been amply demonstrated in controlled environment and field conditions using a variety of plant species (e.g. perennial versus annual, woody versus non-woody, domesticated versus non-domesticated species) (Graham and Miller 2005). However, field studies can be difficult due in-part to a limited ability to control and measure the level of infection by inoculated and endemic species of fungi. Organic acid and phosphatase enzyme exudates increase the availability of inorganic and organic soil P, respectively, by converting solid-phase P to liquid-phase phosphate, which is the main form of P taken up by roots and mycorrhizal hyphae of crops (Richardson et al. 2009).

Nitrogen-fixing plants have been of interest in plantation forestry for many years as primary crop species or as nurse/companion crops to other main species in plantation forests or agro-forestry systems (Forrester et al. 2006). Increased N availability benefits in such systems have been well-demonstrated (Binkley and Giardina 1997), but major deterrents to their adoption on a large scale have been management complexity and economic viability. An overall financial benefit is not obvious unless fertilizer costs are very high or the wood value gained is very high (Turvey and Smethurst 1983). These financial benefits will probably become more obvious if fertilizer and fibre shortages develop. If or when that situation eventuates, plantation forestry and agriculture will need to seriously consider mixed-species systems, for which there are many generic and system-specific research and management questions remaining to be answered.

Ion Flux and Membrane Transporter Technologies

In recent years, the use of ion flux and membrane transporter technologies have started to expand our understanding of the nutritional physiology of trees. Wood formation has a particular dependence on potassium (K), the supply of which to cambial cells is regulated by K^+ channels (Langer et al. 2002). In *Populus tremula,* one transporter was continuously present at a low level, suggesting a house-keeper function, but the levels of two others followed the annual variation in plant growth (Langer et al. 2002). Functioning of theses transporters (and hence uptake of K into cambial and expanding xylem cells) depends on the necessary H^+-gradient being generated by a H^+-ATPase in the plasma membrane, and this response can be initiated within a few hours of the addition of auxin to dormant twigs (Arend et al. 2002). Similar transporter and ion flux studies in tree roots also indicate a key role for H^+-pumping to maintain the electrochemical gradient that drives the fluxes of K and Na (Knowles 2007; Sun et al. 2009). However, when measuring fluxes of these cations, care needs to be exercised in the use of the non-invasive, ion-selective flux microelectrode technology, because one needs to correctly account for the non-ideal, ion-selective behavior of the resins used to make the microelectrodes (Knowles and Shabala 2004).

Using *Populus, Eucalyptus,* and agricultural species (Escalante-Perez et al. 2009; Knowles 2007; Sun et al. 2009), these technologies are now elucidating the genetic and physiological basis to salt sensitivity and tolerance. Regulation of the proton gradient across the plasma membrane reduces Na^+ influx via non-specific cation channels and simultaneously reduces K^+ efflux through depolarization-activated channels. The addition of Ca^{2+} markedly enhances these processes and thereby assists in maintaining K^+/Na^+ homeostasis.

Ion-flux technologies are also available for nitrogen, but not yet for phosphorus. Simultaneous measurements of ammonium, nitrate and proton fluxes around roots of *Eucalyptus nitens* revealed a preference for ammonium, spatial and temporal variations in fluxes in the 20-60 mm region from the root tip, no affect of proximity to root hairs or root laterals, and Michaelis-Menten-style uptake kinetics (Garnett et al. 2001, 2003). Ammonium preference is a more common observation in forest ecosystems than in agricultural systems (Kronzucker et al. 1997; Min et al. 2000). Such results encourage the continued use of ammonium-based fertilizers in forestry. Increased development and use of ion-flux technologies will be needed as we seek to further expand our understanding of plant nutritional physiology and improve fertilizer management, but we need to be cognizant of some current limitations. For example, these methods are mainly suitable for young plants in controlled environments that experience very different growing conditions to field-grown plants, and the lower limits of concentration detection are not as low as the concentrations at which uptake occurs in many forestry and agricultural cropping systems.

Indicators of plantation response to fertilization

There is a well-established method of calibrating soil and plant indicators of potential growth (or yield) response to fertilization (McLaughlin et al. 1999; Smith and Loneragan 1997). This method requires that many fertilizer experiments be established in time and space to capture climatic and landscape variability. Yield of the unfertilized treatment is expressed relative to maximum growth with fertilizer, and these data plotted as a function of the indicator, e.g. a soil or leaf analysis. The value of the indicator at the point where relative yield decreases significantly from below 1.0 (generally taken as 0.90 or 0.95 relative yield) is referred to as the critical value for that indicator. Instead of relative yield, other yield response criteria can also be used, e.g. percent increase in growth due to fertilization.

Fertilizer needs in agriculture commonly take into account soil and plant analyses that are well calibrated. As plantation forestry intensifies and the relative cost of fertilizer increases there will be a need to further develop and apply suitable soil and plant analyses. Appropriate calibrations and their use will not only guide fertilizer use in low- to medium-input systems, but they can also be useful for avoiding the over-use of fertilizers and concomitant environmental problems such as those that occur already in parts of Europe, USA, China and Mexico (Vitousek et al. 2009). Fertilizer practices in forestry should be developed while avoiding over-use.

This protocol for calibrating potential indicators of nutrient deficiency is rarely fully applied in forestry, because resources have often not been available to cater for the long crop cycles and large plot and plant sizes. Some examples are available, and critical indicator values are also inferred, but less-reliably so, from growth and nutrient indicator surveys across operational plantations. Such inferences have also been developed from growth and nutrient relations within just one or a few fertilizer experiments. In the following paragraphs, examples of nutrient limitations in several major plantation regions of the world are described along with the criteria used to predict fertilizer responses.

Pinus plantations, south-eastern USA

A large concentration of forest plantations of *Pinus elliottii* and *P. taeda* (13 M ha) are grown in their native range in the south-eastern USA, and fertilization has been a key component of management intensification during the past five decades (Fox et al. 2007). Nutritionally, these plantations are severely limited by low P and N supply if unfertilized. P-fertilizer is needed at planting (Pritchett et al. 1961), and thereafter a combination of N and P is far better than either nutrient alone (Amateis et al. 2000). The concentration of P in an acid extract (Bray2-P) best discriminated between responsive and non-responsive sites at planting (Ballard and Pritchett 1975). Once established, leaf area index (LAI) is the main diagnostic. A fully stocked stand with stem cross-sectional areas at 1.3 m height greater than 22.9 m^2 ha^{-1} should have an LAI of at least 3.5, unless there are other obvious problems that have altered LAI, e.g. fire, ice, insects etc. (Fox et al. 2007). It is possible to use these criteria, because water is generally less limiting than low N and P supply at this stage of the crop.

Pinus and *Eucalyptus* plantations, Australia

Almost 2 M ha of *Pinus* and *Eucalyptus* plantations are grown in Australia. Where grown on ex-native forest sites that do not have a history of P-fertilization for agricultural production, applications of P fertilizer at planting are essential (Boomsma 1949). Various indices of soil, plant and litter P have been sought for these plantations (May et al. 2009b). Although a common basis for assessment is still lacking, some of these indexes have been calibrated for specific soil-climate-species-management contexts, e.g. $CaCl_2$-extractable P for *Eucalyptus globulus* and *E. nitens* in temperate Australia (Mendham et al. 2002) and total P concentration in litter for *Pinus radiata* in south-east South Australia (May et al. 2009a).

As for *Pinus* plantations in the south-eastern USA, LAI has been recognized as a key determinant of potential growth response to N fertilization in *Pinus radiata* plantations in south-east South Australia (May et al. 2009a) and in *Eucalyptus nitens* plantations in Tasmania (Smethurst et al. 2003). Soil and litter N analyses have also been examined as indicators for these plantations; litter N concentrations in *Pinus radiata* were significantly correlated with response to N-plus-P fertilization (May et al. 2009a). The critical concentration of total N in surface soil was 6 mg g^{-1} for *Eucalyptus nitens* plantations in Tasmania (Smethurst et al. 2004a) and 2 mg g^{-1} for *E. globulus* plantations in Western Australia (White et al. 2009), which illustrates the contextualization required for many critical concentrations based on soil analyses.

Deficiencies of K in *Pinus radiata* occur under some circumstances in Australia, e.g. on ex-farmland where decades of K removals in agricultural products have not been replaced by fertilization (Smethurst et al. 2007). Although foliar analysis appears useful as a diagnostic tool in these circumstances, further refinement of the critical concentrations is warranted to account for soil type, management and climate (Smethurst et al. 2007).

Eucalyptus and *Pinus* plantations, Brazil

The area of eucalypt and pine plantations in Brazil has increased rapidly during the past two decades, and now totals 4 Mha for eucalypts and 2 Mha for pines. Applications of P and K were recognized early as necessary in many regions (Barros et al. 2004). Little or no N fertilization was needed for the first rotation. The incidence and severity of N deficiency on these sites is expected to increase with subsequent rotations, and relative growth of 0.74 to 0.98 has recently been documented in later rotations by age 2 years at 11 sites in São Paulo State (Pulito 2009). At three of these sites, trees had already reached or were close to harvest age of 7 years, and in each of these cases relative growth had increased from 0.74-0.83 at 2 years of age to 1.0 at around 7 years, indicating that the earlier response to N fertilizer had disappeared. The reason for this change was not investigated, and raises the hypothesis that N or another resource became limiting between 2 and 7 years. Specific for either Eucalyptus or Pinus, critical concentrations of organic matter had earlier been proposed as an indicator of the need for N fertilization (Barros et al. 2004), but this criterion was not supported by the Pulito (2009) data. Resin-P for P fertilization, and exchangeable K for K fertilization are still a current recommendation and critical concentrations of these indicators depend on clay content. (Barros et al. 2004).

Soil solutions as indicators of nutrient supply

In agriculture and forestry, the development of soil and foliar analyses as indicators of nutrient deficiency has largely been the responsibility of public organizations like universities and state or national departments of research and extension. However, during the past decade it has become difficult for these organizations to resource this activity, and in many cases it has been dropped as an important objective unless the user-pay principle is applied. Meanwhile, crop genotypes, climate, crop management, and soil conditions have changed. Such changes would be expected to in-turn change the critical concentrations of soil and foliar diagnostics. With food and fibre shortages increasing globally, and system inputs becoming more expensive, including fertilizers, there is a mismatch between the need to use resources more efficiently, and the knowledge base for making fertilizer management decisions. Either traditional systems for developing critical nutrient concentrations need to be re-built, or new technologies need to be developed that are less expensive. This dilemma developed in plantation forestry some years ago and led to consideration of nutrient concentrations in soil solutions as potential indictors that were more generic than traditional, soil-type-specific measures, which rely on strong acid, alkaline or salt extracts (Smethurst 2000).

The desire to interpret nutrient availability from nutrient concentrations in soil solution also motivated others to seek appropriate methods. For example, Barraclough (1989) demonstrated how critical soil solution concentrations for agricultural crops in the UK might be used to derive more accurate critical

concentrations of more traditional soil indices by accounting for volumetric soil water content (θ_v). A soil of $\theta_v = 0.34$ was estimated to have a critical Olsen P value of 7 mg g^{-1}, in comparison to a drier soil ($\theta_v = 0.30$) requiring a higher critical Olsen P value of 23 mg g^{-1}. This motivation and operational simplicity were also behind development of a dilute calcium chloride extract (0.01 M $CaCl_2$) as an indicator of nutrient availability in European agricultural soils; this solution mimics the ionic strength and pH of soil solutions (Houba et al. 2000). Such an extract was particularly useful for identifying P deficiency in pastures (Dear et al. 1992) and temperate eucalypt plantations (Mendham et al. 2002).

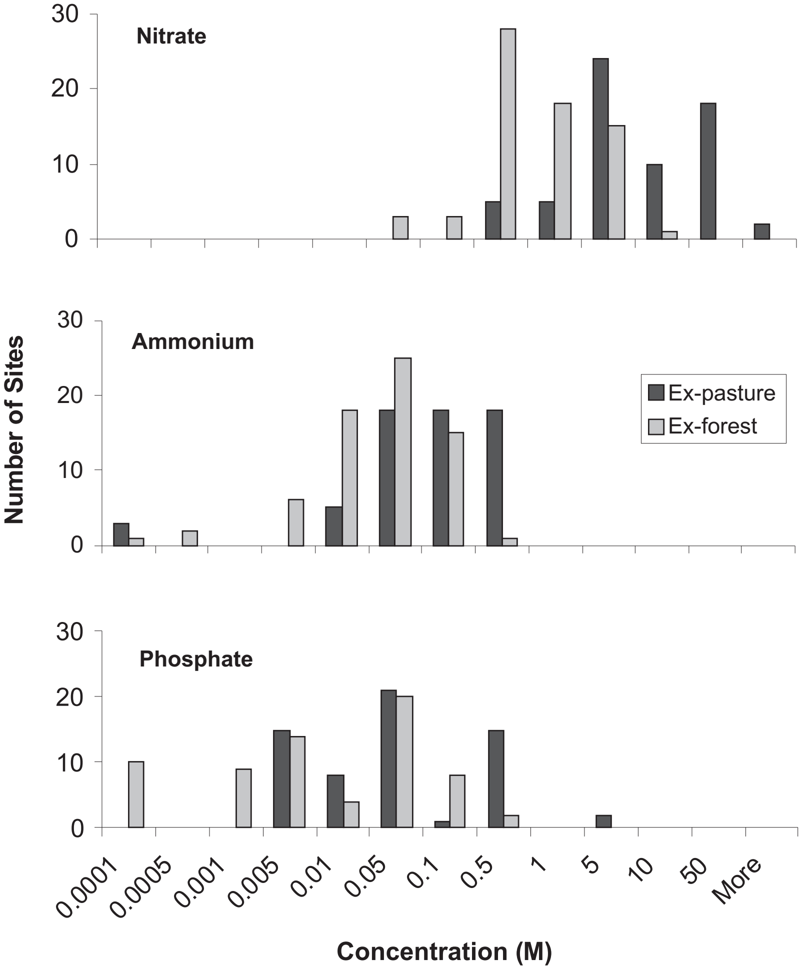
In a research context, soil solution technology has proven more useful than traditional measures of soil fertility where well-established calibrations are lacking (e.g. Smethurst et al. 2001; 2007). Can this technology be developed also as an operational method? The principle of using soil solutions for inferring nutrient deficiencies relies on three main steps. Firstly, the concentration of the inorganic nutrient needs to be measured in a paste extract. Secondly, this concentration may need adjusting for potential dilution effects that can occur during preparation of the paste. The adjusted concentration is an estimate of the concentration in bulk soil solution. Thirdly, the bulk soil solution concentration is interpreted on the basis of that which is required at root surfaces to maintain near-optimum growth.

There is a possibility that the soil solution method could be adapted to low-cost, portable equipment by using simple centrifugation or suction methods to extract the paste solution and by analyzing the solution using portable water analysis equipment (Osborne et al. 2001). The essential aspects of this method were demonstrated in a survey of forest plantations in four regions of Australia, where a large part of the variation in soil fertility is attributed to fertilizer history, in particular whether there had been a pasture phase accompanied by fertilizer inputs. Paste samples were prepared using de-ionized water, and solution was extracted using porous ceramic tips (Rhizon© solution samplers purchased from Eijkelkamp) to which a partial vacuum had been applied. Solutions were analyzed for NH_4, NO_3, PO_4 and K on a portable spectrophotometer designed for water analysis (Spectroquant Nova 60 Photometer© purchased from Merck). Due to buffering by the solid phase, concentrations of NH_4, PO_4 and K in soil solution were assumed to be altered little by the addition of water during preparation of the paste, but NO_3 concentrations were adjusted to account for the dilution effect.

Frequency distributions of concentrations of NH_4, NO_3, and PO_4 indicated that higher values were more common on ex-pasture sites than on ex-forest sites (Fig. 2). In a separate study, soil solution NH_4 and NO_3 correctly discriminated between 6 responsive and 2 non-responsive *E. nitens* plantations when fertilized with N.

This level of discrimination was better than that achieved by the commonly used KCl extract (Smethurst et al. 2004a). Soil solution P and its surrogate $CaCl_2$-P were also good discriminators of P responsive sites (Mendham et al. 2002). Even if the soil solution approach is adopted, it will not eliminate the need for field experiments; instead, its potential to reduce the need for field experiments and to provide a more generic approach to soil fertility assessment warrants further testing.

Fig. 2 Frequency distribution of surface soil NO_3 (top), NH_4 (middle) and PO_4 (bottom) concentrations measured in Australian forest plantations grown on ex-pasture and ex-forest sites. Concentrations were measured using a low-cost, portable nutrient anlaysis system (Osborne et al. 2001).



Conclusions and Knowledge Gaps

This review places several aspects of forest fertilization developments in an agricultural context, and identifies knowledge gaps:

1. Fertilizer use in intensive plantation forestry does not approach the usage seen in the most intensive pasture (dairy) or annual cropping systems on a per ha per year basis.
2. However, intensive plantation forestry systems are similar to some biennial or perennial agricultural systems in the length of the crop cycle and the rates of fertilizer applied per application.
3. Less intensive plantations systems have much longer rotations than in agriculture and much lower rates of fertilizer use, and plantation forestry overall occupies a small portion of the landscape compared with agriculture.
4. Fertilization strategies in forestry consider internal and external nutrient cycling and deep rooting.
5. As an option for improving nutrient use efficiency, both forestry and agriculture will need to further develop rhizosphere and mixed-species technologies.
6. Forest scientists have contributed significantly to developing methods of plant culture that maintain stable internal nutrient concentrations. As a research tool, this development should continue to improve our understanding of nutrient-growth relationships.
7. The development of plant production models that include the mechanistic simulation of nutrient supply, uptake and weed competition are at a similar early stage of development in both agriculture and forestry. Nitrogen modeling is more advanced than other nutrients.
8. Plantation forestry lacks a mechanistic basis for evaluating base cation availability that accounts for Al-pH-root interactions, which is also the situation in agriculture. Further developments in this field could assist in rationalizing the use of lime.
9. Traditional concepts of nutrient use efficiency in forestry have recently been challenged and need clarifying in the context of fertilizer management for food, fiber and biofuel production.
10. There is an on-going need to develop calibrations of traditional types of soil and foliar analyses, but, in some countries, organizations that have developed these calibrations in the past are finding it difficult to resource further work.
11. Testing soil solution approaches of assessing soil fertility are warranted,

because they offer a more generic and affordable approach that might reduce the need for field experimentation.

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Role of nutrients in human health: New insights

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Abstract The importance of nutrition as a determinant of health status of the population has been well recognized. Nutrition is a dynamic science. Our understanding of functions of known nutrients is still not complete. There is a wealth of new information emerging from research on hither to unexplored roles of nutrients and the definition of nutrient itself is under scanner. Among the bio active phytochemicals, carotenoids other than non vitamin A precursors like lutein and zeaxanthin have shown strong evidence in preventing or delaying the age related muscular degenerative disease and lycopene in prostrate cancer. Curcumin is another phytochemical, which is a remarkable inhibitor of oral cancer and cell growth. Tannins and Phytates which were considered as anti nutritional factors have now been found to help in reducing the risk of cancers and cardiovascular diseases. Consequent to westernization of Indian diets, the intake of salt is on the increase and this is not only risk factor for hypertension and also creating imbalance in the sodium/potassium ratio. Recent study had indicated that increased potassium intake and reduced sodium intake can reduce the risk of hypertension. Dietary intake of Potassium among Indians is one tenth of what is recommended. Until recently, the role of nutrients in preventing chronic diseases was not systematically considered in defining dietary recommendations. Therefore there is urgent need to look in to the recommended dietary allowances for these emerging nutrients for various physiological groups.

Keywords Cancer • cardiovascular diseases • nutrition • phytochemicals • vitamins.

Introduction

Nutrition is a dynamic science. Our understanding of functions of known nutrients is still not complete. There is a wealth of new information emerging from research on hither to unexplored roles of nutrients and the definition of nutrient itself is under scanner. The importance of nutrition as a determinant of health status of the population has been well recognized. Diet can modify the pathophysiological processes of various metabolic disorders and can be an effective preventive strategy for various disease processes most of which are known to involve

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oxidative damage. Both nutrient and non-nutrient components of the diet have been recognized for their anti-oxidant and other potential benefits. New scientific evidence gave support to the concept that nutrients were not only essential to the growth, development, and maintenance of tissues, but were also linked to the expression of genetic information, the effectiveness of the immune system, the prevention of cell damage, and in general, to increased resistance to many chronic diseases and even some infectious diseases. This link to health maintenance and disease prevention resulted in a renewed interest and excitement in nutrition that was now expanded beyond the domain of classical nutritional deficiencies. The realization came about that a diet and its nutritional consequences could have a profound influence on the control and prevention of many chronic conditions such as osteoporosis, cardiovascular disease, high blood pressure, and cancer, as well as play an important role in many oral diseases and pathoses such as dental caries, periodontal disease, salivary gland dysfunction, and soft tissue lesions. The present paper is the documentation of beneficial effects of some of the phyto chemicals and emerging new roles of minerals.

Carotenoids

Plant carotenoids are red, orange, and yellow lipid-soluble pigments found embedded in the membranes of chloroplasts and chromoplasts. Their color is masked by chlorophyll in photosynthetic tissues, but in late stages of plant development these pigments contribute to the bright colors of many flowers and fruits and the carrot root. Carotenoids protect photosynthetic organisms against potentially harmful photo oxidative processes and are essential structural components of the photosynthetic antenna and reaction center complexes (Glen and Scolnik 2009). In plants, some of these compounds are precursors of abscisic acid (ABA), a phytohormone that modulates developmental and stress processes (Koornneef, 1986).

Carotenoids with provitamin A activity are essential components of the human diet, and these are abundantly present in Indian foods (Baskarachary et al. 1995; Bhaskarachary et al. 2008). Early observational studies suggested an inverse relationship between lung cancer risk and beta-carotene intake, often assessed by measuring blood levels of beta-carotene (Peto et al. 1981; Ziegler 1989). Dietary intakes of total carotenoids, lycopene, beta-cryptoxanthin, lutein, and zeaxanthin, but not beta-carotene, were associated with significant reductions in risk of lung cancer in a 14-year study of more than 27,000 Finnish male smokers (Holick et al. 2002), while only dietary intakes of beta-cryptoxanthin and lutein and zeaxanthin were inversely associated with lung cancer risk in a 6-year study of more than 58,000 Dutch men (Voorrips et al. 2000).

The results of several prospective cohort studies suggest that lycopene-rich diets are associated with significant reductions in the risk of prostate cancer, particularly more aggressive forms (Giovannucci 2000). In a prospective study of more than 47,000 health professionals followed for eight years, those with the highest lycopene intake had a risk of prostate cancer that was 21 percent lower than those with the lowest lycopene intake (Giovannucci et al. 1995). Those with the highest intakes of tomatoes and tomato products (accounting for 82 percent of total lycopene intake) had a risk of prostate cancer that was 35 percent lower and a risk of aggressive prostate cancer that was 53 percent lower than those with the lowest intakes. Similarly, a prospective study of Seventh Day Adventist men found those who reported the highest tomato intakes were at significantly lower risk of prostate cancer (Mills et al. 1989), and a prospective study of U.S. physicians found those with the highest plasma lycopene levels were at significantly lower risk of developing aggressive prostate cancer (Gann et al. 1999). Because they are very soluble in fat and very insoluble in water, carotenoids circulate in lipoproteins along with cholesterol and other fats. Evidence that low-density lipoprotein oxidation plays a role in the development of atherosclerosis led scientists to investigate the role of antioxidant compounds like carotenoids in the prevention of cardiovascular disease (Kritchevsky 1999). The results of several prospective studies indicate that people with higher intakes of carotenoids-rich fruits and vegetables are at lower risk of cardiovascular disease (Sahyoun et al. 1996; Rimm et al. 1995; Gaziano et al. 1995; Osganian et al. 2003), it is not yet clear whether this effect is a result of carotenoids or other factors associated with diets high in carotenoids-rich fruits and vegetables.

Degeneration of the macula, the center of the eye's retina, is the leading cause of blindness in older adults. Unlike cataracts, in which the diseased lens can be replaced, there is no cure for age-related macular degeneration (AMD). Therefore, efforts are aimed at disease prevention or delaying the progression of AMD. The only carotenoids found in the retina are lutein and zeaxanthin. Lutein and zeaxanthin are present in high concentrations in the macula, where they are efficient absorbers of blue light. By preventing a substantial amount of the blue light entering the eye from reaching the underlying structures involved in vision, lutein and zeaxanthin may protect against light-induced oxidative damage, which is thought to play a role in the pathology of age-related macular degeneration (Snellen et al. 2002; Krinsky et al. 2003). Epidemiological studies provide some evidence that higher intakes of lutein and zeaxanthin are associated with lower risk of AMD (Mares-Perlman et al. 2002). To date, the available scientific evidence suggests that consuming at least 6 mg/day of dietary lutein and zeaxanthin from fruits and vegetables may decrease the risk of age-related macular degeneration (Seddon et al. 1994; Mares-Perlman et al. 2001, 2002). Four large prospective studies found that men and women with the highest intakes of foods rich in lutein and zeaxanthin, particularly spinach, kale, and broccoli, were 18-50 percent less likely to require cataract extraction (Brown et al. 1999; Chasan-Taber et al. 1999) or develop cataracts (Lyle et al. 1999; Christen et al. 2003; Moeller et al. 2008).

Phytates

Until recently, phytates were considered to be antinutrients since they prevented the absorption of other nutrients. Although they are not toxic and consuming them does not cause serious changes in our body, they were regarded negatively due to their ability to bind minerals in the intestine, such that the absorption of certain minerals, such as iron, calcium and magnesium was reduced throughout the body and the benefit received from these nutrients, which are fundamental to our health was less, which in the case of iron, could result in anaemia. Despite having been questioned, this view has changed and current opinion is that, in the correct proportions, phytates can play a beneficial role in our health. Once they have been absorbed, they can exert a biological effect, either inside or outside the intestine. If the phytic acid binds to lead or other metals, which are harmful to the body such as cadmium, it helps to detoxify it because it prevents it from assimilating in the blood and facilitates their elimination in our faeces without passing through the bloodstream from the intestine. Otherwise, they can cause irreversible damage to the central nervous system. Phytates' ability to bind themselves to other elements is highly beneficial for the human body since it helps to prevent the appearance of conditions such as diabetes, heart disease and kidney stones (Jariwalla 2001).

Inositol hexaphosphate (IP (6)) is a naturally occurring polyphosphorylated carbohydrate, abundantly present in many plant sources and in certain high-fiber diets, such as cereals and legumes. In addition to being found in plants, IP(6) is contained in almost all mammalian cells, although in much smaller amounts, where it is important in regulating vital cellular functions such as signal transduction, cell proliferation, and differentiation. For a long time IP (6) has been recognized as a natural antioxidant. Recently IP (6) has received much attention for its role in cancer prevention and control of experimental tumor growth, progression, and metastasis. In addition, IP(6) possesses other significant benefits for human health, such as the ability to enhance immune system, prevent pathological calcification and kidney stone formation, lower elevated serum cholesterol, and reduce pathological platelet activity (Vucenik and Shamsuddin 2003; Vucenik and Shamsuddin 2006). Specifically, the interaction of phytic acid with certain types of protein in the large intestine can help to reduce the activity of the bacterial enzymes involved in developing cancer of the colon. Furthermore, it binds with cholesterol and triglycerides, reducing their absorption and, consequently, their concentration in the blood, and also helps to control the rhythm of intestinal evacuation. Likewise, phytates prevent the formation of oxalate salts in the kidneys, which are responsible for forming kidney stones.

Polyphenols

Plant polyphenols, a large group of natural antioxidants, are serious candidates in explanations of the protective effects of vegetables and fruits against cancer and cardiovascular diseases. Epidemiologic studies are useful for evaluation of the human health effects of long-term exposure to physiologic concentrations of polyphenols, but reliable data on polyphenols contents of foods are still scarce. Polyphenols occur in all plant foods and contribute to the beneficial health effects of vegetables and fruit. Their contribution to the antioxidant capacity of the human diet is much larger than that of vitamins. The total intake of polyphenols in a person's diet could amount to 1 gram a day, whereas combined intakes of beta-carotene, vitamin C, and vitamin E from food most often is about 100 mg a day. Phenolic acids account for about one third of the total intake of polyphenols in our diet, and flavonoids account for the remaining two thirds. (Williamson and Manach 2005).

Fruit and beverages such as tea and red wine represent the main sources of polyphenols. Despite their wide distribution, the healthy effects of dietary polyphenols have come to the attention of nutritionists only in the last years. The main factor responsible for the delayed research on polyphenols is the variety and the complexity of their chemical structure. Emerging findings suggest a large number of potential mechanisms of action of polyphenols in preventing disease, which may be independent of their conventional antioxidant activities. Isoflavones (genistein and daidzein, found in soy) have significant effects on bone health among postmenopausal women, together with some weak hormonal effects. Monomeric catechins (found at especially high concentrations in tea) have effects on plasma antioxidant biomarkers and energy metabolism. Procyanidins (oligomeric catechins found at high concentrations in red wine, grapes, cocoa, cranberries, apples, and some supplements such as Pycnogenol) have pronounced effects on the vascular system, including but not limited to plasma antioxidant activity. Quercetin (the main representative of the flavonol class, found at high concentrations in onions, apples, red wine, broccoli, tea, and Ginkgo biloba) influences some carcinogenesis markers and has small effects on plasma antioxidant biomarkers in vivo, although some studies failed to find this effect. Compared with the effects of polyphenols in vitro, the effects in vivo, although significant, are more limited (Williamson and Manach 2005).

Harper et al. (2009) showed that Genistein, resveratrol, and the high-dose combination treatments suppressed prostate cancer. Polyphenol treatments decreased cell proliferation and insulin-like growth factor-1 (IGF-1) protein expression in the prostate. In addition, genistein as a single agent induced apoptosis and decreased steroid receptor coactivator-3 in the ventral prostate. Genistein and resveratrol, alone and in combination, suppress prostate cancer development in the SV-40 Tag model. Regulation of SRC-3 and growth factor signaling proteins are consistent with these nutritional polyphenols reducing cell proliferation and increasing apoptosis in the prostate. The health benefits of Epigallocatechin-3-gallate, one of the most abundant and widely studied catechin found in green tea (*Camellia sinensis*) catechins are becoming increasingly recognised. Amongst the proposed benefits are the maintenance of endothelial function and vascular homeostasis and an associated reduction in atherogenesis and cardiovascular disease risk (Moore et al. 2009). Atherogenic dyslipidaemia associated with a pro-inflammatory pro-thrombotic state in metabolic syndrome and related risk of fatty liver, arthritis, neurodegenerative disorders and certain types of cancers are ideal therapeutic targets for bioactive phytochemicals, particularly flavonoids and tanins which can combat oxidative stress induced damage at a sub-cellular level (Soory 2009).

Sulphur compounds

Currently reliance on natural products is gaining popularity to combat various physiological threats including oxidative stress, cardiovascular complexities, cancer insurgence, and immune dysfunction. The use of traditional remedies may encounter more frequently due to an array of scientific evidence in their favor. Garlic (*Allium sativum*) holds a unique position in history and was recognized for its therapeutic potential. Recent advancements in the field of immunonutrition, physiology, and pharmacology further explored its importance as a functional food against various pathologies. Extensive research work has been carried out on the health promoting properties of garlic, often referred to its sulfur containing metabolites i.e. allicin and its derivatives. Garlic in its preparations are effective against health risks and even used as dietary supplements such as age garlic extract (AGE) and garlic oil etc. Its components/formulations can scavenge free radicals and protect membranes from damage and maintains cell integrity. It also provides cardiovascular protection mediated by lowering of cholesterol, blood pressure, anti-platelet activities, and thromboxane formation thus providing protection against atherosclerosis and associated disorders. Besides this, it possesses antimutagenic and antiproliferative properties that are interesting in chemopreventive interventions (Butt et al. 2009).

Non-pharmacological treatment options for hypertension have the potential to reduce the risk of cardiovascular disease at a population level. Animal studies have suggested that garlic reduces blood pressure, but primary studies in humans and non-systematic reviews have reported mixed results. Reid et al. (2008) meta-analysis revealed that garlic preparations are superior to placebo in reducing blood pressure in individuals with hypertension. Garlic reduced systolic blood pressure (SBP) by 16.3 mm Hg (95% CI 6.2 to 26.5) and diastolic blood pressure (DBP) by 9.3 mm Hg compared with placebo in patients with elevated SBP. Meta-analysis suggests that garlic is associated with blood pressure reductions in patients with an elevated SBP although not in those without elevated SBP (Reinhart et al. 2008).

Garlic has been used for centuries for treating various ailments, and its consumption is said to reduce cancer risk and its extracts and components effectively block experimentally induced tumors (Hirsch et al. 2000; Ried et al. 2008). The study conducted by Oommen et al. (2004) demonstrated allicin-induced apoptosis of cancer cells are novel since allicin has not been shown to induce apoptosis previously. This study also provides a mechanistic basis for the antiproliferative effects of allicin and partly account for the chemopreventive action of garlic extracts reported by earlier workers.

Glucosinolates (GLSs) are found in *Brassica* vegetables. Examples of these sources include cabbage, brussels sprouts, broccoli, cauliflower and various root vegetables (e.g. radish and turnip). A number of epidemiological studies have identified an inverse association between consumption of these vegetables and the risk of colon and rectal cancer. Animal studies have shown changes in enzyme activities and DNA damage resulting from consumption of brassica vegetables or isothiocyanates, the breakdown products of GLSs in the body (Verkerk et al. 2009). Broccoli consumption mediates a variety of functions including providing antioxidants, regulating enzymes and controlling apoptosis and cell cycle. The organosulfur chemicals namely glucosinolates and the S-methyl cysteine sulphoxide found in broccoli in concert with other constituents such as vitamins E, C, K and the minerals such as iron, zinc, selenium and the polyphenols namely kaempferol, quercetin glucosides and isorhamnetin are presumably responsible for various health benefits of broccoli (Vasanthi et al. 2009).

Potassium

Potassium intake prevents from ailments like stroke, blood pressure, anxiety and stress, muscular strength, metabolism, heart and kidney disorders, water balance, electrolytic functions, nervous system and other general health problems. Until recently, humans consumed a diet high in potassium. However, with the increasing consumption of processed food, which has potassium removed, combined with a reduction in the consumption of fruits and vegetables, there has been a large decrease in potassium intake which now, in most developed countries, averages around 70 m mol day^{-1}, i.e. only one third of our evolutionary intake. Much evidence shows that increasing potassium intake has beneficial effects on human health. Epidemiological and clinical studies show that a high-potassium diet lowers blood pressure in individuals with both raised blood pressure and average population blood pressure. Prospective cohort studies and outcome trials show that increasing potassium intake reduces cardiovascular disease mortality. This is mainly attributable to the blood pressure-lowering effect and may also be partially because of the direct effects of potassium on the cardiovascular system. A high-potassium diet may also prevent or at least slow the progression of renal disease. An increased potassium intake lowers urinary calcium excretion and plays an important role in the management of hypercalciuria and kidney stones and is likely to decrease the risk of osteoporosis. Low serum potassium is strongly related to glucose intolerance, and increasing potassium intake may prevent the development of diabetes that occurs with prolonged treatment with thiazide diuretics (Feng et al. 2008**)**. Dietary intake of Potassium among Indians is one tenth of what is recommended. Therefore consuming various varieties of fruit and vegetables will augment the potassium levels effectively.

Other minerals

Boron, chromium, manganese, nickel, tin, vanadium, molybdenum, arsenic, lithium, aluminium, strontium, cesium and silicon are regarded as new trace elements in the sense that they have only recently been considered essential in human diets. These elements are the subject of exciting research in animals, particularly ruminants, where they have been shown to be essential in one or more species. For example, ruminants feeding on grass grown in soil where molybdenum levels are abnormally high have demonstrated an increased tendency to exhibit copper deficiency. However, for many of these new trace elements (e.g., Mn) there is no evidence that abnormally low or high dietary intakes cause substantial nutritional problems in human populations (Weisell 1991).

Conclusions

Nutrition science and the quest to improve human diet have undergone a quiet but major transition over the last 50 years. The first half of the 20th century was centered on the discovery and characterization of essential nutrients, vitamins, amino acids, and cofactors that were indispensable constituents of a healthy diet. These discoveries greatly influenced the focus of applied nutrition, which centered first on defining the minimum needs of essential nutrients in humans, and second in defining diets that provided those minimum amounts needed to maintain health. In the second half of the 20th century, environmental factors began to gain prominence as important determinants of human health. It witnessed the increasing influence of nutritional epidemiology in discovering these diet–health associations, and deciphered the mystery by performing some of the unique experiments on human beings. Some of the phytochemicals such as flavonoids, phenolic acids, carotenoids, sulphur compounds, minerals, trace elements showed beneficial biological activity in chronic degenerative diseases. These should be considered along with the known nutrients for sustaining human health. Until recently, the role of nutrients in preventing chronic diseases was not systematically considered in defining dietary recommendations.Therefore, there is urgent need to look in to the recommended dieatry allownaces for these emerging nutrients for various physcilogical groups.

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Impact of potassium nutrition on postharvest fruit quality: Melon (*Cucumis melo* L) case study

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Abstract Among the many plant mineral nutrients, potassium (K) stands out as a cation having the strongest influence on quality attributes that determine fruit marketability, consumer preference, and the concentration of critically important human-health associated phytonutrients. However, many plant, soil, and environmental factors often limit adequate uptake of K from the soil in sufficient amounts to satisfy fruit K requirements during development to optimize the aforementioned quality attributes. The objectives of this review are 1) to summarize published study abstracts on the effects of soil and/or foliar K fertilization as well as diverse K forms, on fruit phytonutrient concentrations; and 2) to illustrate the important role of K forms on fruit quality with a case study of *Cucumis melo* L (muskmelon) fruit produced with optimal soil applied K. The muskmelon studies will compare commercial sources (forms) of K applied to examine seasonal effects (spring vs. autumn) and the number of foliar K applications during fruit development on fruit marketability (maturity, yield, firmness, soluble solids, sugars, relative sweetness), consumer preference attributes (sugar content, sweetness, texture), and phytochemical concentrations (K, ascorbic acid, and b-carotene concentrations). Numerous studies have consistently demonstrated that specific K fertilizer forms, in combination with specific application regimes, can improve fruit quality attributes. Potassium fertilizer forms in order of effectiveness (Glycine (Gly)-complexed K = $K_2SO_4 \geq KCl >$ no K > KNO_3) when applied wet (foliar or hydroponic) vs. dry (soil) were generally superior in improving fruit marketability attributes, along with many human-health nutrients. The muskmelon case study demonstrated that two K

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forms: Gly-complexed K and K_2SO_4, combined with a silicone-based surfactant, applied weekly, as a foliar spray, during fruit development, from both autumn and spring-grown plants, had the greatest impact on improving fruit marketability attributes (maturity, yield, firmness, and sugars), as well as fruit quality attributes (human-health bioactive compounds K, ascorbic acid, and β-carotene). Among several foliar applied K salts studied under field conditions so far, salts with relatively low salt indices appeared to have the greatest impacts on fruit quality when applied during the mid- to late-season fruit development periods.

Keywords Fruit • foliar application • human health • marketability • potassium fertilizers • sugar • vitamins • yield

Introduction

Potassium (K) is an essential plant mineral element (nutrient) having a significant influence on increasing many human-health related quality compounds in fruits and vegetables (Usherwood, 1985). Although K is not a constituent of any organic molecule or plant structure, it is involved in numerous biochemical and physiological processes vital to plant growth, yield, quality and stress (Marschner, 1995; Cakmak, 2005). In addition to stomatal regulation of transpiration and photosynthesis, K is also involved in photophosphorylation, transportation of photoassimilates from source tissues via the phloem to sink tissues, enzyme activation, turgor maintenance, and stress tolerance (Usherwood, 1985; Doman and Geiger, 1979; Marschner, 1995; Pettigrew, 2008). Adequate K nutrition has also been associated with increased yields, fruit size, increased soluble solids and ascorbic acid concentrations, improved fruit color, increased shelf life, and shipping quality of many horticultural crops (Geraldson 1985; Lester et al. 2005, 2006; Kanai et al. 2007).

Even though K is abundant in many soils, the bulk of soil K is unavailable to plants, in part, because the pool of plant-available K is much smaller compared to the other forms of K in the soil. Potassium exists in several forms in the soil such as mineral K (90-98% of total), nonexchangable K, exchangeable K, and dissolved or solution K (K^+ ions), and plants can only directly take up solution K (Tisdale et al. 1985). Uptake in turn depends on numerous plant and environmental factors (Tisdale et al. 1985; Marschner, 1995; Brady and Weil 1999). For instance, adequate soil moisture supply is necessary to facilitate diffusion of K (which usually accounts for > 75% of K movement) to plant roots for uptake. Mass flow, which also accounts for some soil K transport, also requires sufficient water in the soil. Skogley and Haby (1981) found that increasing soil moisture from 10 to 28% more than doubled total soil K transport. Therefore, soil moisture deficits can limit soil K transport as well as uptake into the plant, thereby causing K deficiency.

Soil properties also have a strong influence on K availability. For instance, clay soils typically have high K-fixing capacities and thus often show little response to soil-applied K fertilizers because much of the available K quickly binds to clays (Tisdale et al. 1985; Brady and Weil 1999). Such K fixation can help reduce leaching losses, and be beneficial in the long-term as storage reservoirs of K for subsequent crops. Sandy soils, on the other hand tend to have a low K supplying power because of their low cation exchange capacities.

In calcareous soils, Ca^{2+} ions tend to exist in high concentrations and dominate clay surfaces, and even though this can limit K sorption and increase solution K, high concentrations of cationic nutrients (particularly Ca^{2+} and Mg^{2+}) tend to limit K uptake by competing for binding sites on root surfaces. Consequently, crops grown on highly calcareous soils can show K-deficiency symptoms even though the soil test may report sufficient K (Havlin et. al. 1999).

Potassium uptake also depends on plant factors, including genetics and developmental stage (vegetative versus reproductive stages; Rengel et al. 2008). In many fruiting species, uptake occurs mainly during vegetative stages, when ample carbohydrate supply is available for root growth and uptake processes. Competition for photoassimilates between developing fruits and vegetative organs during reproductive growth stages can limit root growth/activity and K uptake. Under such conditions, increasing soil K fertilization may not be enough to alleviate this developmentally-induced deficiency partly because of reduced root growth/activity during reproductive development and also because of competition from other cations for binding sites on roots (Marschner 1995).

In the literature, much confusion exists regarding the benefit of K fertilization due to different K forms utilized, soil vs. foliar applications, the environment (season), plus frequency of applications during fruit growth and development stages. This review will (1) summarize some of the published abstracts on K fertilization of several fruit crops, and (2) illustrate the influence of adequate K nutrition on fruit quality with a case study of supplemental foliar K fertilization of *Cucumis melo* L (muskmelon) grown on soil with seemingly adequate K content. Special attention is given to the effectiveness (comparison) of various K fertilizer sources, and soil vs. foliar application on fruit quality.

Fruit studies comparing K sources

Although many examples have been reported on the positive effects of K fertilization improving fruit disease control, yield, weight, firmness, sugars, sensory attributes, shelf-life, and human bioactive compound concentrations, the scientific literature also contains examples of studies with conflicting results of the beneficial effects of K fertilization on fruit quality (Table 1). These conflicting results cannot be resolved, but they can be explained by differences in modes of fertilization [soil applied (dry) vs. foliar, fertigation or hydroponic applied (wet)], and differences in forms of K fertilizer e.g. Glycine-complexed K, versus K_2SO_4, KCl, or KNO_3 from K fertilization. A review of published abstracts (Table 1), spanning the last twenty years, eight particular studies [apple (*Malus X Domestica;* Hassanloui, et al. 2004), cucumber (*Cucumis sativus;* Umamaheswarappa and Krishnappa 2004), mango (*Mangifera indica;* Rebolledo-Martinez et al. 2008), pear (*Prunus communis;* Johnson et al. 1998), bell pepper (*Capsicum annuum;* Hochmuth et al. 1994), strawberry (Fragaria X ananassa; Albregts et al. 1996), and watermelon (*Citrullus lanatus;* Locascio and Hochmuth 2002; Perkins-Veazie et al. 2003)] stand out, because of their conclusions: there is 'little or no change' (i.e. improvement) from K fertilization on fruit quality. However, except for the apple study, these studies have a common denominator in that potassium was applied directly to the soil and in many cases little information was given regarding timing of application with regard to crop phenology or soil chemical and physical properties such as pH, calcium and magnesium contents, and textures (sandy vs. clay). These properties are known to influence soil nutrient availability and plant uptake, and soil fertilizer K additions under such conditions may have little or no effect on uptake, yield and fruit quality (Tisdale et al. 1985; Brady and Weil 1999). In a number of studies involving several fruiting crops (e.g. cucumber, mango, and muskmelon) where soil-applied fertilizer K was compared to foliar K applications, the latter approach consistently resulted in improved fruit quality attributes whereas the former approach generally had little or no effects (Demiral and Koseoglu 2005; Lester et al. 2005; Lester et al. 2006; Jifon and Lester 2009; Table 1). Furthermore, in studies where several fertilizer K salts were evaluated, fruit quality improvements appeared to depend on timing of application as well as fertilizer K formulation. For instance, when mid- to-late season soil or foliar K applications were made using KNO_3 there were little or no improvements in fruit marketable or human-nutritional quality attributes and in some instances, these attributes were actually inferior compared to fruit from control plots (Jifon and Lester 2009).

Foliar Fertilization with different K salts: Case studies with muskmelon (*Cucumis melo* L.)

As discussed above, plant and soil factors can limit soil-available, as well as plant uptake of K even though soil tests may report sufficient K. This situation is particularly acute for crops grown on highly calcareous soils whereby such uptake limitations can lead to K-deficiency symptoms, reduced yield and poor quality. In such cases where soil-applied fertilizers would be ineffective, due to high fixation, the only way to improve plant K uptake has been through foliar application of water-soluble K fertilizers, such as potassium chloride (KCl) or potassium nitrate

Table 1 Review of published abstracts on the influence of potassium (K): effects by crop, K application, and K form on fruit attributes

Crop	**K application**	**K form**[a]	**Attributes (improved)**[b]	**Reference**[c]
Apple *(Malus X domestica)*	Soil	KCl; K_2SO_4; K_2SO_4	Color, firmness, sugar; Size, color, firmness, sugars; Wt. yield, firmness, sugars	(Nava et al. 2009) ; El-Gazzar (2000); Attala (1998)
Apple	Foliar	Unknown; KCl	Size, color, firmness, sugars; No change	Wojcik (2005); (Hassanloui et al. 2004)
Banana *(Musa sp.)*	Soil	Unknown; KCl	Quality; Size, sugars, acid	Naresh (1999); (Suresh & Hasan 2002)
Citrus *(Citrus sinesis)*	Foliar	KCl, KNO_3; unknown; K_2SO_4	No change; Yield, quality; Quality	Haggag (1990); (Dutta et al. 2003); (Shawky et al. 2000)
Citrus *(Citrus reticulata)*	Soil	Unknown; Unknown	Yield, quality; Quality, shelf-life	(Lin et al. 2006); (Srivastava et al. 2001)
Citrus *(Citrus reticulata)*	Foliar	KCl >KNO_3	Peel thickness, quality	(Gill & Singh 2005)
Cucumber *(Cucumis sativus)*	Soil	K_2SO_4 > KCl; KCl	Amino acids, quality; No change	(Guo et al. 2004); (Umamaheswarappa & Krishnappa 2004)
Cucumber	Foliar	KCl >KNO_3	"Quality", disease tolerance	(Magen et al. 2003)
Grapes *(Vitis vinifera)*	Soil	K_2SO_4	"Quality", sensory	(Sipiora et al. 2005)
Guava *(Psidium guajava)*	Soil	Unknown	Yield, weight, "quality"	(Ke & Wang 1997)
Guava	Foliar	K_2SO_4 > KCl	Acidity, "quality"	Dutta (2004)
Kiwifruit *(Actinidia deliciosa)*	Soil	K_2SO_4 > KCl	Firmness, acid, grade	He (2002)
Litchi *(Litchi chinensis)*	Foliar	KNO_3	Wt., yield,	(Ashok & Ganesh 2004)
Mango *(Mangifera indica)*	Soil	KNO^3	No change	Simoes (2001)

Crop	K application	K form[a]	Attributes (improved)[b]	Reference[c]
Mango	Foliar	KNO_3; Unknown	No effect; Texture, flavor, color, shelf-life	(Rebolledo-Martinez et al. 2008); Shinde (2006)
Muskmelon *(Cucumis melo)*	Soil	Unknown	Yield	(Demiral & Koseoglu 2005)
Muskmelon	Foliar	Gly-amino-K; Gly-amino-K > KCl; Gly-amino-K = $K_2 SO_4$ > KCl > KNO_3	Firmness, vitamins; Firmness, sugars, vitamins; Firmness, vitamins, sugars, yield, marketable fruit	(Lester et al. 2006); Lester (2006); Jifon & Lester (2009)
Nectarine *(Prunus persica)*	Soil	Unknown	Firmness, shelf-life, reduced cracking	(Zhang et al. 2008)
Okra *(Abelmoschus esculentus)*	Foliar	Naphthenate-K	Chlorophyll, protein, carotene	(Jahan et al. 1991)
Passionfruit *(Passiflora edulis)*	Hydroponic	$K_2 SO_4$	Yield, seed number, "quality"	(Costa-Araujo et al. 2006)
Papaya *(Carica papaya)*	Soi	Unknown	Weight, sugars, "quality"	Ghosh & Tarai (2007)
Pears *(Prunus communis)*	Soi	$K_2 SO_4$	No change	(Johnson et al. 1998)
Phalsa *(Grewia subinaequalis)*	Foliar	$K_2 SO_4$	Size, wt., "quality"	(Singh et al. 1993)
Pepper *(Capsicum annuum)*	Soil	KCl; $K_2 SO_4$; $K_2 SO_4$ > KNO_3; $K_2 SO_4$	Little change; Pungency, "quality"; Pungency, yield, wt.; "quality"	(Hochmuth et al. 1994): (Ananthi et al. 2004); (Golcz et al. 2004); El-Masry (2000)
Pepper	Hydroponics	KNO_3	No change	(Flores et al. 2004)
Pineapple *(Ananas comosus)*	Soil	KCl	Vit. C, and reduced internal browning	(Herath et al. 2000)
Pomegranate *(Punica granatum)*	Foliar	$K_2 SO_4$ > KCl	Growth, yield, "quality"	Muthumanickam & Balakrishnamoorthy (1999)
Strawberry *(Fragaria X ananassa)*	Soil; Fertigation	KCl; KCl >KNO_3	No change; "quality"	(Albregts et al. 1996); (Ibrahim et al. 2004)
Strawberry	Hydroponics	$K_2 SO_4$	Yield , total quality	(Khayyat et al. 2007)
Tomato *(Lycopersicon esculentum)*	Soil	KCl; $K_2 SO_4$; $K_2 SO_4$;	Lycopene; "quality"; Yield, earliness, quality	(Taber et al. 2008); (Si et al. 2007); Hewedy (2000)
Tomato	Fertigation/ soilless	KCl >KNO_3; KCl >KNO_3; $K_2 SO_4$; Unknown; Unknown	Appearance, quality; Yield, "quality"; Carotenoids, vit.E, Antioxidants; Lycopene; "quality"	Chapagain & Wiseman (2003); Chapagain & Wiseman (2004); (Fanasca et al. 2006); (Li et al. 2006); (Yang et al. 2005)
Tomato	Foliar	Unknown	Growth, protein, vit. C, sugar, acid	(Li et al. 2008)
Vegetables	Soil	$K_2 SO_4$ > KCl	Dry wt., vit. C	(Ni et al. 2001)
Watermelon *(Citrullus lanatus)*	Soil	KCl KCl	No change; No change	Locascio & Hochmuth (2002); (Perkins-Veazie et al. 2003)

[a] Forms from different studies are separated by a semi-colon; K form attributing to improved quality greater than another K form is indicated by the > symbol; [b] Attributes from different studies are separated by a semicolon, the word “quality” indicates the authors' listed no specific attributes, or the attributes were too numerous to list, [c] References from different studies are separated by a semi-colon

(KNO_3). Controlled environment studies have indeed shown that supplementing soil-derived K supply with foliar K applications during the fruit development period can improve fruit quality and that differences may exist among K compounds for foliar feeding (Lester et al. 2005; 2006). To further explore the degree to which differences among some K salts may influence fruit quality, field studies were conducted near Weslaco, TX using a netted muskmelon (*Cucumis melo* L.) variety 'Cruiser'. Soils in this important fruit-producing region are predominantly calcareous with free calcium carbonate ($CaCO_3$), which tends to buffer soil pH to around 7.5 to 8.5. Base saturation is generally ~100%, and cation exchange is dominated by calcium. Average pre-plant soil concentrations of major cations were 7300, 660, 440, and 190 mg kg^{-1} for Ca, K, Mg and Na respectively. All studies were conducted during the spring (February-May) growing season following standard commercial muskmelon production practices for this region (Dainello 1996). Foliar K treatments (Fig.1) were applied weekly (between 0500 and 0800 a.m.) starting at fruit set, and continued till fruit maturation using K from various sources namely: potassium chloride (KCl), potassium nitrate (KNO_3), potassium sulfate (K_2SO_4), Gly-complexed K (glycine amino acid complexed K - Potassium Metalosate™, 20% K; Albion Laboratories, Inc, Clearfield, Utah), monopotassium phosphate (PeaK™, 24% K, Rotem BKG LLC, Ft Lee, NJ), and potassium thiosulfate (KTS™, 20% K, Tessenderlo Kerley Inc., Phoenix, AZ). Treatment solutions were formulated to supply the equivalent of ~4 kg K ha^{-1} per week and each solution contained a non-ionic surfactant (Silwet L-77 at 0.3% v/v; Helena, Collierville, TN).

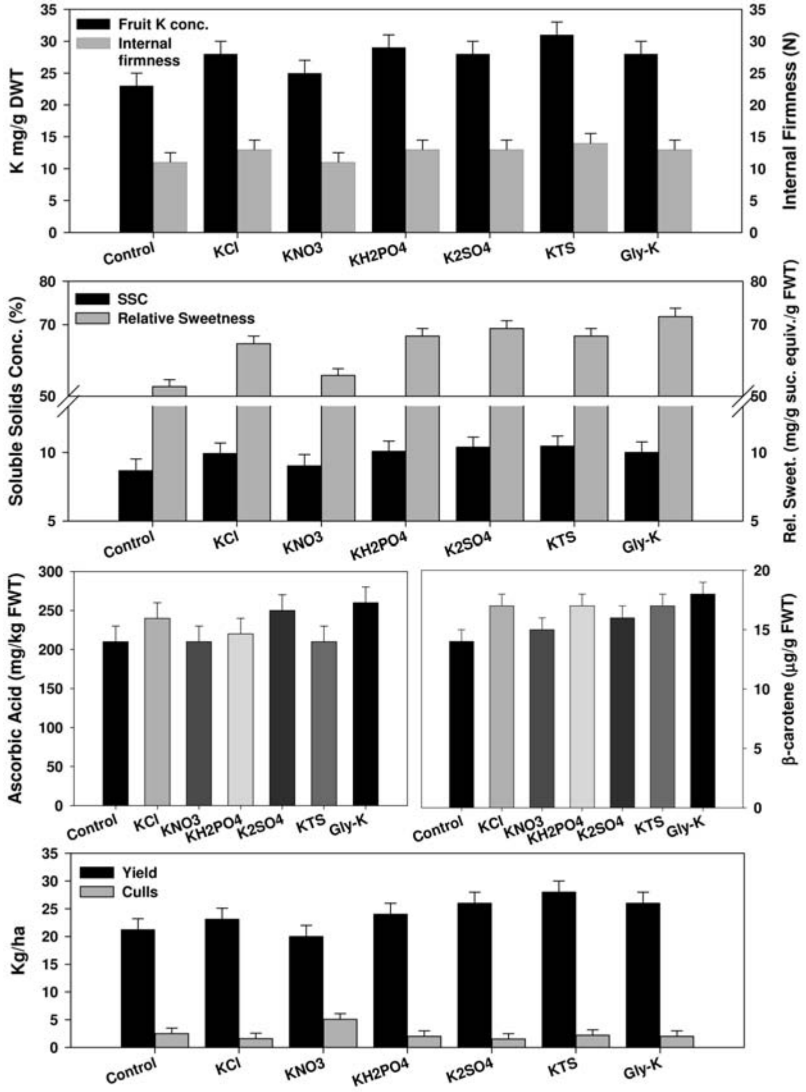
Leaf K concentrations measured during the fruit maturation period were significantly lower (~13 g kg^{-1}) than the values measured before fruit set (~37 g kg^{-1}). Leaf K concentrations were also lower than the recommended sufficiency ranges (20-40 g kg^{-1}; Hochmuth and Hanlon 1995), even though pre-plant soil analysis indicated very high soil K concentrations (>600 mg kg^{-1}). At fruit maturity, tissue (leaf, petiole, stem and fruit) K concentrations of foliar K-treated plants were on average ~19% higher than those of control plants. This observation suggests that plant K uptake from this calcareous soil was not sufficient to maintain tissue K concentrations within sufficiency levels, and that the K supplying power of this soil may be low even though pre-plant soil K content was high. The low K supplying capacity of this soil is further indicated by the high pH and high Ca and Mg concentrations since these conditions are known to suppress soil K availability and plant uptake (Marschner 1995; Brady and Weil 1999). Fruit quality parameters (soluble solids concentration, total sugars, sweetness, and the phytochemical compounds - ascorbic acid and beta-carotene) responded positively to foliar K applications (Fig. 1). However, no clear trends were apparent with regard to the most suitable salt for all quality parameters except for KNO_3 whose effects were nearly always statistically similar to those of the control treatments. The lack of significant differences between controls and KNO_3-treated plants was probably related to timing of treatment applications with respect to crop phenology. Treatments were applied during the reproductive growth stages (mid- to late-season), and foliar fertilization with KNO_3 significantly increased leaf N concentrations (~30%) compared to the other K salts; the resulting stimulation of vegetative growth at the expense of roots and fruits probably accounted for the marginal effect on fruit quality through competition for assimilates (Way and While 1968; Davenport 1996; Neuweiler 1997; Keller et al. 1999; Wade et al. 2004). Fruit mesocarp tissue firmness, a good indicator of shipping quality, texture and shelf life (Harker et. al. 1997), was improved by foliar K applications. This may be related to increased tissue pressure potential (Lester et al. 2006). Foliar K-treated plots had slightly higher yields (Fig. 1), however, this effect was only significant in one of the three years, and with one K salt (potassium thiosulfate). Additionally, the average number of cull fruit with defects such as poor external rind (net) development or small size was generally higher in plots treated with foliar KNO_3 than in plots treated with the other K forms (Fig. 1).

In addition to plant and environmental factors, critical properties of potential K salts for foliar nutrition are solubility, salt index (SI) and point of deliquescence (POD). A suitable balance among these properties is required to maximize nutrient absorption into plant tissues and to minimize phytotoxicity effects. Highly soluble salts are preferred since this means faster cuticular penetration and smaller volumes of solution needed for application. The salt index of a fertilizer material is defined as the ratio of the increase in solution osmotic pressure produced by the fertilizer material to that produced by the same mass of $NaNO_3$ (Mortvedt, 2001). The SI gives an indication of which fertilizer salts (usually those with higher SI) are most likely to cause injury and compares one fertilizer formulation with others regarding the osmotic (salt) effects (Mortvedt, 2001). The SI of some common K salts are, KCl, 116; KH_2PO_4, 8.4; K_2SO_4, 43; potassium thiosulfate, 68 (Mortvedt, 2001).

A common production problem not observed in this study, which is likely temperature related, is the foliar 'burning' effect, which is frequently observed when using foliar applied salts such as KCl (Swietlik and Faust, 1984). Burning of leaves occurs when salts accumulate on the surface and are not absorbed. Rates of absorption are highest when relative humidity is 80% or higher (Schonherr and Luber, 2001). In this field study leaf 'burn' symptoms were not observed with any of the treatments, in part, because all treatments were applied between 0500 and 0800 when high air relative humidities, (>80%), low air temperatures (<25°C) and low wind speeds (< 0.45 $m \cdot s^{-1}$) prevailed.

Point of deliquescence of a foliar fertilizer salt determines the rate at which the applied salt is absorbed by plant tissues. Point of deliquescence is the humidity

Fig. 1 Effects of various K fertilizer sources (potassium chloride - KCL, potassium nitrate - KNO_3, potassium sulfate - K_2SO_4, gylcine amino acid potassium - Gly –K, monopotassium phosphate - KH_2PO_4, and potassium thiosulfate - KTS) foliar applied weekly to field-grown, fruit-bearing muskmelon plants during fruit development on various marketability and quality attributes of fruit. All plants had sufficient soil fertilization. Relative sweetness = 1.8 (mg/ g FWT fructose) + 0.7 (mg/g FWT glucose) + 1.0 (mg/g FWT sucrose). Data are means ± SD and are separated by the LSMEANS procedure of SAS (Statistical Analysis System, Cary, NC, USA) at $P \leq 0.05$ (Jifon and Lester 2008)



over a saturated salt solution containing solid salt (Schönherr and Luber 2001). If air humidity is higher than the POD, salts will remain dissolved in solution and absorption will proceed rapidly. However, when air humidity is below the POD (i.e. drier air), salts will re-crystallize, resulting in slower uptake and increasing the potential for salt injury. Reported POD values for some common K salts are K_2CO_3, 44%; KCl, 86%; KNO_3, 95%; and KH_2PO_4, 97% (Schönherr and Luber, 2001). Several studies have shown that phytotoxicity effects are common when compounds such as KCl, with high salt indices and relatively high point of deliquescence, are used and this is more pronounced when they are applied under conditions of high temperature and/or low air humidity (Schönherr and Luber, 2001).

K fertilizer application: Seasonal influence and silicone-based surfactant

Muskmelon fruit firmness (external - under the epidermis, at the equatorial region; and internal middle-mesocarp - at the equatorial plane, using a penetrometer) from autumn and spring fruit-bearing plants, sprayed with K, was higher than that of fruit from control plants (no foliar K) regardless of season, surfactant use, or K form (Fig 2). Similar beneficial effects of foliar K, from KH_2PO_4, on tomato fruit (*Lycopersicon esculentum* Mill.) firmness has been shown (Chapagain and Wiesman, 2004), but the mechanisms for improved firmness were not discussed. Increased melon fruit firmness from exogenously-applied K is not due to improved membrane integrity or cell wall stability, as is the case with exogenously-applied calcium (Lester and Grusak 1999), since K does not become part of any structural component of plant tissues as does Ca (Cooke and Clarkson 1992). The increase in melon fruit firmness resulting from foliar applied K is increased (more positive) fruit-tissue pressure potential (ψ_p) (Table 2). Mesocarp tissue ψ_p was significantly higher in all K-treated, compared to non-treated control fruits. Addition of surfactant increased the effect of foliar K application on mesocarp tissue ψ_p (+46% and +150% for Gly amino acid complexed K (Gly-K) and KCl, respectively), although surfactant use was not always associated with increased fruit firmness. A significant positive correlation was observed between fruit-tissue ψ_p and internal fruit firmness (r = 0.259; P = 0.01). The increased ψ_p of K-treated fruit, compared to controls, resulted, at least in part, from greater accumulation of other osmolytes (e.g. sugars; Fig. 2) in addition to increased K concentrations in fruit cells (Lester et al., 2006). Since there were no differences in tissue water potential (ψ_w), a more negative solute potential (ψ_s) resulted in higher ψ_p ($\psi_p = \psi_w - \psi_s$) values in K-treated, compared to control fruits (Lester et al. 2006). Pressure potential was found to be positively correlated with SSC (r = 0.232; P = 0.01), total sugars (r = 0.276), fruit sucrose and glucose concentrations (P = 0.05) (Lester et al. 2006). Positive correlations among tissue solute

Fig. 2 Effect of growing season (autumn or spring) and two sources of K (potassium chloride - KCL, gylcine amino acid potassium –Gly –K) with or without a silicon-based surfactant (S) foliar applied weekly to glasshouse-grown fruit-bearing muskmelon plants during fruit development on various marketability and quality attributes of fruit. All plants had sufficient soil fertilization. Relative sweetness = 1.8 (mg/ g FWT fructose) + 0.7 (mg/g FWT glucose) + 1.0 (mg/g FWT sucrose). Data are means ± SD and are separated by the LSMEANS procedure of SAS (Statistical Analysis System, Cary, NC, USA) at $P \leq 0.05$ (Lester et al. 2006)

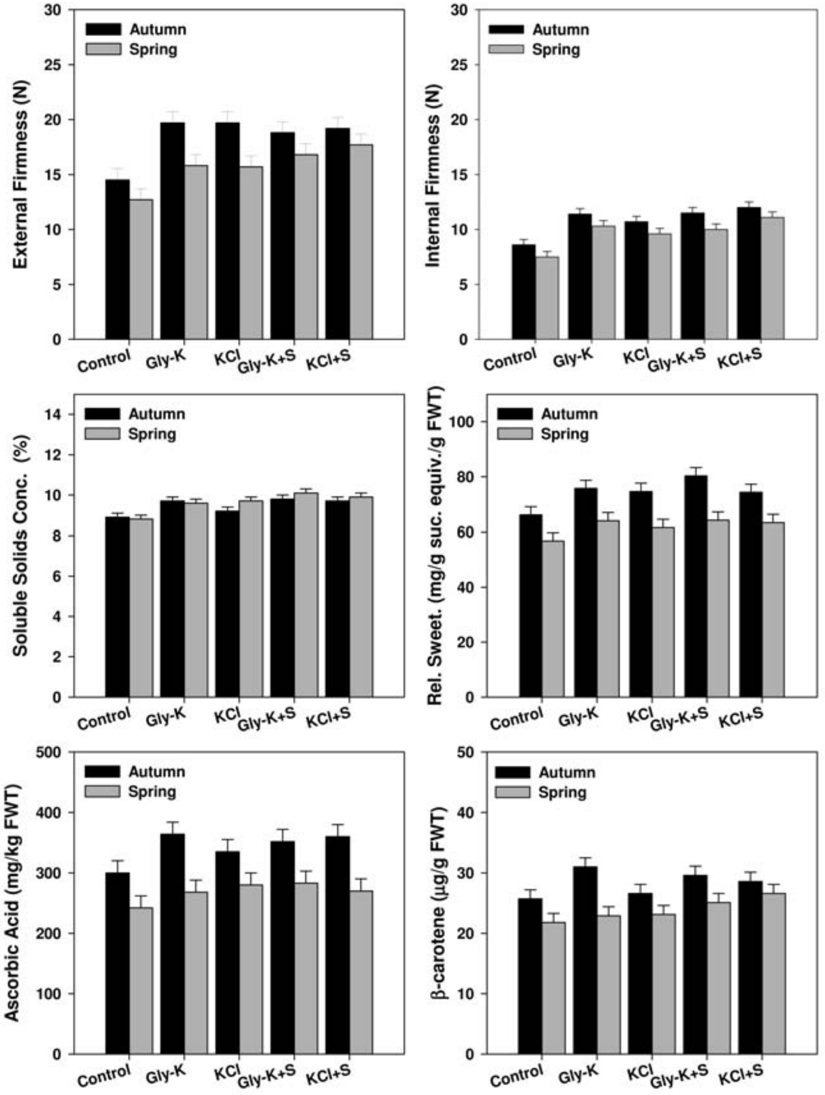


Table 2 Influence of weekly supplemental foliar K - glycine amino acid-potassium (Gly-K) and potassium chloride (KCl) applied with or without a surfactant (S), to fruit-bearing plants grown with adequate soil K concentrations, on muskmelon fruit tissue pressure potential (Lester et. al. 2006)

Treatment	Fruit Pressure ψ_p (MPa)[a]
Gly-K	-0.018b[b]
KCl	-0.034c
Gly-K +S	0.003a
KCl + S	0.011a
Control	-0.064d

[a] The more positive the pressure potential the firmer the fruit. [b] Means followed by the same letter are not significantly different by the LSMEANS procedure of SAS (Statistical Analysis System, Cary, NC, USA) at P< 0.05

concentration, turgor and firmness have also been reported for potato (*Solanum tuberosum* L.) tubers (Beringer et al. 1983) and apples (Tong et al. 1999).

Fruit sugars as measured by soluble solids concentrations and relative sweetness were higher in K-treated compared to control fruit in both autumn and spring grown fruit (Fig. 2). Fruits from plants treated with Gly-K also tended to have slightly greater soluble solids concentrations and relative sweetness levels than those treated with KCl regardless of silicone-based surfactant use or season. Previous studies on supplemental K fertilization have reported a variety of responses including an increase in fruit sugar levels (e.g. Chapagain and Wiesman 2004; Daugaard and Grauslund 1999; Johnson et al. 1998), no effect on fruit SSC (Flores et al. 2004; Hartz et al. 2001) and improved yields (Hartz et al. 2005). Hartz et al. (2001, 2005) also found that K fertigation reduced the incidences of yellow shoulder and internal white tissue disorders in tomato but did not influence fruit SSC or juice color. Hartz (2001, 2005) attributed the absence of any response of fruit SSC to other overriding factors, such as cultivar and irrigation management, which potentially masked any K effects. Lin et al. (2004) found that supplemental K fertilization of melon in soil less culture increased fruit sucrose content but had no effect on fruit fructose and glucose concentrations. However, in the Lester et al. (2006) study, netted muskmelon fruit sucrose, glucose and fructose levels were increased by supplemental foliar K fertilization. It is worth noting that foliar Gly-complexed K treatments without surfactant had higher fruit fructose concentrations than the Gly-complexed K treatments with a silicone-based surfactant. A plausible explanation for this observation maybe silicone-based surfactant interference with the catalytic role of amino acids on invertase activity. Silicone-based reagents synthesize aminophosphonates (Boduszer and Soroka 2002) which act as antagonists of amino acids, inhibiting enzyme metabolism affecting the physiological activity of the cell (Kafarski and Lejcak 1991). Acid invertase (EC 3.2.1.26), found in melon fruits (Lester et al. 2001) is responsible for sucrose hydrolysis to fructose and glucose. Amino acids are catalysts in this hydrolysis reaction (Quick and Schaffer, 1996). It is likely the silicone-based surfactant interfered with the catalytic activity of the amino acid cofactor, thus down-regulating acid invertase allowing sucrose phosphate synthase (EC 2.3.1.14), the sucrose-synthesizing enzyme in melons (Lester et al. 2001), to remain active. Sucrose phosphate synthase specifically utilizes K as a cofactor to synthesize sucrose from glucose and fructose (Lester et al. 2001). The relative levels of sucrose and fructose in fruit also have important implications for consumer preference (relative sweetness) since fructose is perceived to be up to 80% sweeter than sucrose.

Total ascorbic acid and b-carotene were generally higher in fruits treated with K than in control fruits (Fig. 2). However, there were no consistent K source effects on these quality parameters. The beneficial effects of supplemental K probably resulted from a combination of improved leaf photosynthetic CO_2 assimilation, assimilate translocation from leaves to fruits, improved leaf and fruit water relations, increased enzyme activation and substrate availability for ascorbic acid and b-carotene biosynthesis all associated with adequate K nutrition (Hopkins 1963; Gross 1991). At present, it is unclear how high K concentrations in melon fruit increases ascorbic acid and beta-carotene concentrations, but increased synthesis through enzyme activation is a possible mechanism. In general, use of a surfactant increased fruit tissue concentrations of ascorbic acid and b-carotene (Fig. 2). However, the surfactant effect was not always consistent with both K forms; requiring further investigations into various surfactants applied with and without K foliarly to fruit-bearing plants. Use of specific foliar applied K forms, as a means to improve the antioxidant capacity (ascorbic acid and b-carotene, respectively) of melon fruits is a readily applicable, low-technology approach to improve the human wellness attributes of current commercially produced melon cultivars.

The beneficial effects of supplemental foliar K applications to fruit-bearing plants on melon fruit quality parameters were consistently positive regardless of growing season – spring or autumn. However, fruit produced in autumn had higher fruit firmness, ascorbic acid, b-carotene, total sugars and SSC (Fig. 2). Mechanisms for the improved quality parameters in autumn- compared to spring-grown fruit are still uncertain since average daily temperatures and cumulative heat units were slightly higher in autumn (~33°C and 728, respectively) than in spring (~28°C and 601, respectively). Cumulative photosynthetic photon flux during fruit development (from pollination to final harvest) was higher in spring ($982\ mol{\cdot}m^{-2}$) than in autumn ($637 mol{\cdot}m^{-2}$). New findings suggest that weather and climate play key roles in the human-health bioactive compounds in fruits (Lester 2006). These studies highlight how global climate change might affect the nutritional properties of food crop and how, through the use of foliar applied K, growers may counteract these effects.

Number of foliar K applications

Supplemental foliar K applications resulted in earlier maturity of treated fruit compared to controls (Fig. 3). While this important marketability trait is not reported in K-treated fruit and the mechanisms for this effect are unclear, similar K-induced effects on fruit K concentrations and firmness have been reported (Chapagain and Wiesman 2004). Earlier maturity is a desirable economic trait in muskmelon production regions where adequate solar radiation flux can permit sufficient soluble solids accumulation in fruits before full-slip (abscission). Also, increased fruit firmness realized with weekly K foliar applications > biweekly applications > no foliar K application (Fig. 3), results in a melon fruit having an extended shelf-life which is another important marketability trait.

Fruit K contents resulting from the supplemental foliar application, increasing with weekly applications > biweekly applications of K compared to control fruit, was accompanied by increased fruit sugar levels (Fig. 3). Leaf photosynthesis rates are reported to increase with increased leaf K concentrations and this could be one mechanism of increased sugar contents in fruit (Terry and Ulrich 1973; Peoples and Koch 1979; Pettigrew 1999). However, leaf photosynthesis rates measured during the melon fruit maturation were similar among control and K-treated fruits (data not shown). Increased phloem loading, transport rate and/or unloading of sugars could also account for the increased fruit sugar levels, although it is uncertain whether this is a direct effect (enhanced phloem unloading in fruits) or an indirect effect (e.g. enhanced sucrose synthesis in source leaves) (Doman and Geiger 1979; Peel and Rogers 1982). Asche et al. (2001) provided evidence for faba bean (*Vicia faba* L.) indicating that K^+ channels are involved in sugar unloading. Potassium-induced increases in fruit sugar levels have also been reported in hydroponically grown muskmelon plants (Lin et al. 2004) however, the mechanism for this effect was also unclear. Although a threshold tissue K concentration for attaining optimum fruit sugar levels has not been established, our melon data (Lester et al. 2005 and 2006; Jifon and Lester 2009) provide additional evidence that fruit sugar concentrations can be increased through supplemental foliar K sprays.

Antioxidants ascorbic acid, derived from glucose (Hopkins 1963), and beta-carotene significantly increased with weekly K applications > biweekly applications > no foliar K application (Fig 3). Of the two antioxidants, beta-carotene dramatically responded to K foliar fertilizations increasing 70% and 100% with biweekly and weekly applications respectively. A benefit to the plant for having heightened levels of antioxidants is improved plant tolerance to various

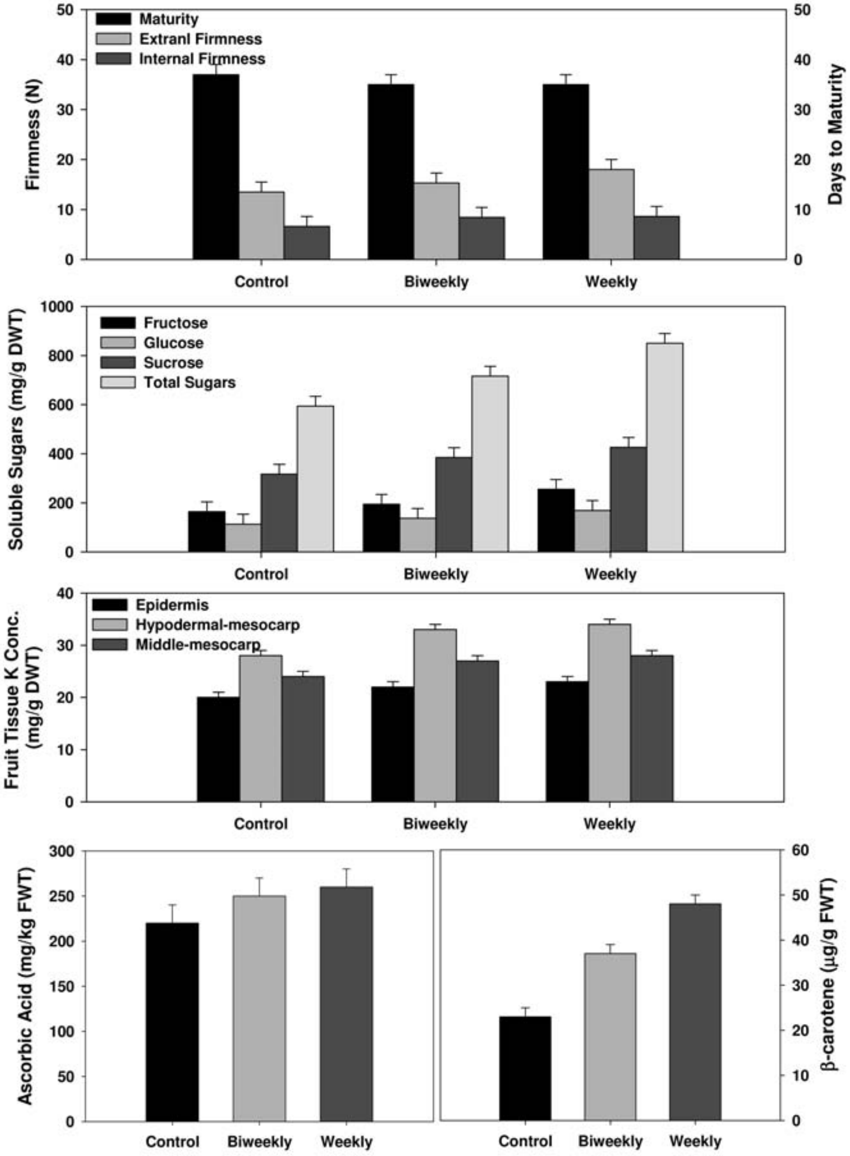


Fig. 3 Effect of number of foliar applications of K (gylcine amino acid potassium) applied to glasshouse-grown, fruit-bearing muskmelon plants during fruit development on various marketability and quality attributes of fruit. All plants had sufficient soil fertilization. Data are means ± SD and are separated by the LSMEANS procedure of SAS (Statistical Analysis System, Cary, NC, USA) at $P \leq 0.05$ (Lester et al. 2005)

environmental stresses such as drought, low temperature, salinity, and sun burning all of which trigger cellular oxidative stress (Hodges et al. 2001; Cakmak 2005). The mechanism for K-induced oxidative stress tolerance is through increased ascorbic acid and beta carotene antioxidant activity. Ascorbic acid acts as an antioxidant by donating electrons and hydrogen ions thus reducing reactive oxygen species or free radicals. And beta-carotene is an accessory pigment in green tissues involved in photon capture protecting chlorophyll molecules from photo-oxidation due to excessive light thus reducing bleaching and sun burning and exhibits good radical-trapping antioxidant behavior under low (2%) oxygen conditions in fruit and root/tuber tissues (Gross 1991).

In melon fruit, the enzyme lipoxygenase (EC 1.13.11.12) has been associated with cellular membrane breakdown and fruit senescence through enhanced production of free radicals, however, this effect is minimized in fruit with high beta-carotene concentrations (Lester 1990). Ascorbic acid and beta-carotene also play similar important roles as antioxidants in humans when consumed in diets. Enhancing their accumulation in fruits, through carefully-timed, controlled K foliar fertilization to fruit-bearing plants will enhance the human wellness potential of melons (Lester and Eischen 1996; Larson 1997).

Conclusions

Supplementing soil K supply with foliar K applications to fruit-bearing plants improves fruit quality by increasing firmness, sugar content, ascorbic acid and beta-carotene levels. Among the K salts, KNO_3 has little or no beneficial effects on fruit quality when applied during fruit maturation, perhaps due to a dilution effect resulting from N stimulation of vegetative growth at the expense of roots and fruits. Perhaps foliar fertilization KNO_3 would be more beneficial during the vegetative growth stages when N is most needed for development of leaves with high photosynthetic capacity. The fruit quality improvements summarized in this review were obtained by implementing a simple low cost management tool that growers can easily adopt; resulting in nutritionally enrich fruits which, at little or no extra retail cost, benefits the consumer. Future research is needed to validate these findings in commercial field trials under different production environments (temperate vs. tropical) and productions systems (conventional vs. organic), and evaluate the effect of different K forms (glycine amino acid complexed K versus potassium chloride and others) on marketable quality and health-bioactive compound quality attributes of various fruits.

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Effect of potassium on fruit quality and their storage life

SK Mitra • SS Dhaliwal

Abstract Potassium has been described as the quality element and it plays a pivotal role in ensuring optimum quality of agricultural produce. Potassium has two main functions in the plant. Firstly it has an irreplaceable role in the activation of enzymes that are fundamental to metabolic processes especially the production of proteins and sugars. Only small amounts of K are required for this biochemical function. Secondly, K maintains the water content and thus helps in maintaining the turgor of cells as a biophysical role. Turgid cells maintain the leaf's vigour so that photosynthesis proceeds efficiently. The relationship between water and nutrient content of the cell controls the movement of both, through the plant and the transport of sugars produced by photosynthesis to storage organs of fruit. Potassium is required in much higher quantities for its physiological functions than for its biochemical role in plants. Fertilization with K is the first step to achieve the required quality standards. A great deal of research has established the beneficial effects of balanced nutrient supply, including adequate K, on the quality of the harvested produce. This is especially true for nutritional properties such as the protein content, oil, and vitamins and other functional aspects. Crops with an adequate supply of K have more weight, better appearance, taste and flavor, and also produce disease and pest free food. Numerous on-farm trials within IPI projects have proved that balanced fertilization with K helps the farmer to produce food, which fulfills the different quality criteria. Potassium improves the product's appearance and reduces the risk of rejection when the produce is offered for sale in the buyer's market.

Keywords Fruit quality • processing quality • storage life of fruits • mineral and vitamins

Introduction

Fruits are the health capsules being the main source of vitamins and minerals

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besides providing other dietary elements like carbohydrates, proteins, fiber, fats, vitamins and enzymes. India is endowed with favorable tropical, sub-tropical and temperate climate which is very conducive for producing high quality fruits round the year (Perrenoud 1990; Shamshiri and Usha 2004) in which more than 50 kinds of fruits are grown and important of them being Banana, citrus, grapes, mango, papaya, pineapple, passion fruits and litchi etc (Tandon and Kemmler 1986). Although the country has achieved fairly good production level of fruits to the tune of 43 million tones, but it is hardly sufficient to meet the 92 million tones, the total requirement of the country (Kumar et al. 2006). This warrants increase in production and productivity of fruit crops.

Judicious use of nutrients (N, P_2O_5 and K_2O) and their management is often regarded as one of the important aspects to increase the productivity of horticultural crops particularly fruit crops (Hardter and Krauss 1999; Hochmuth et al. 1994; Kafkafi et al. 2001). The only way to increase fruit production is to increase crop efficiency i.e. fruit yield per unit land area and cropping efficiency i.e. fruit yield and returns per unit of time. Efficient and rationale use of the fertilizers is imperative not only for obtaining more yields per unit area on a sustainable basis, but also to conserve the energy. The quantum jump in fruit production has to come from increase in productivity by intensive cultivation of fruit crops (Marshner 1995; Marshner et al. 1996). Apart from the fruit production, fruit quality is another aspect that has gained relative importance in modern day horticulture.

Even though K is abundant in many soils, the bulk of soil K is unavailable to plants, because the plant-available K pool is much smaller compared to the other forms of K in the soil. Potassium exists in several forms in the soil such as mineral K (90–98% of total), non-exchangeable K, exchangeable K, and dissolved or solution K (K^+ ions), and plants can only directly take up solution K (Lester et al. 2010). Uptake in turn depends on numerous plant and environmental factors (Usherwood 1985), which may limit K supply during the development stages, hence adversely affecting the quality attributes. For instance, adequate soil moisture supply is necessary to facilitate diffusion of K (which usually accounts for >75% of K movement) to plant roots for uptake. Mass flow, which also accounts for some soil K transport, also requires sufficient water in the soil. Marschner et al. (1996) found that increasing soil moisture from 10 to 28 percent doubled total soil K transport. Therefore, soil moisture deficits can limit soil K transport as well as uptake by the plants, thereby causing K deficiency.

The availability of K in the soil is strongly influenced by soil properties like pH, EC, OC, alkalinity, salinity, texture and CEC. For instance, clay soils typically have high K-fixing capacities and often show little response to soil-applied K fertilizers because much of the available K quickly adsorbs to clays (Sullivan et al. 1974). Such K fixation can help in reducing the leaching losses and can be beneficial in the long-term as storage reservoirs of K for subsequent crops. Sandy soils, on the other hand tend to have a low K supplying power because of their low cation exchange capacities. In calcareous soils, Ca^{2+} ions tend to exist in high concentrations and dominate clay surfaces, and limit K sorption. High concentrations of cationic nutrients (particularly Ca^{2+} and Mg^{2+}) tend to limit K uptake by competing for binding sites on root surfaces. Consequently, crops grown on highly calcareous soils can show K-deficiency symptoms even though the soil test may report sufficient K (Kafkafi et al. 2001).

Potassium uptake also depends on plant factors, including genetics and developmental stage (vegetative and reproductive stages) (Marschner et al. 1996). Deficiency symptoms of K have been reported in many fruit crops. Management of K in light and porous soils with less organic matter is very important. In such cases application of heavy doses of organic matter will facilitate the retention of K by soil. Application of organic manures exclusively to meet the demand of the entire nutrient requirement of the crop or judicious and conjunctive use of both organic and inorganic is the option available to supply nutrients to fruit crops.

In many fruiting plant species, uptake of K occurs mainly during vegetative stages, when ample carbohydrate supply is available for root growth and uptake processes. Competition for photoassimilates between developing fruits and vegetative organs during reproductive growth stages can limit root growth and K uptake. Under such conditions, increasing soil K fertilization may not be enough to alleviate this developmentally-induced deficiency partly because of reduced root growth/activity during reproductive development and also because of competition from other cations for binding sites on roots (Marschner 1995).

Special attention needs to be given to the effectiveness of various K fertilizer sources and soil and foliar application of K on fruit quality. With the introduction of high yielding varieties and hybrids of fruits, responses to higher doses of fertilizer application have increased (Shamshiri and Usha 2004). Plant nutrients like N, P_2O_5 and K_2O available at high concentrations are often lost due to leaching, erosion, and volatilization due to limited time of absorption at different growth stages and the capacity of the soil to retain and release the applied nutrients (Tiwari et al. 1999). Among different nutrient sources in the soil, water-soluble sources of nutrients are in increased demand for fertigation (Sullivan et al. 1974; Tandon and Kemmler 1986).

Fruit crops are heavy feeders of potassium (K) and remove K higher than that of nitrogen (N) and phosphorus (P_2O_5) (Table1). Potassium, along with other macronutrients like N and P is an essential nutrient which is taken up by the crops in relatively high amounts compared to other nutrients (Gene et al. 2010; Haldter and Krauss 1999; Shawky et al. 2004). Potassium increases both yield as well as quality of fruit crops. Apart from it, potassium enhances the ability of fruit crops

Table 1 Nitrogen, phosphorus and potassium removal by fruit crops

Crop	Yield (t ha^{-1})	Nutrient removal (kg ha^{-1}) by fruit crops		
		N	P_2O_5	K_2O
Banana	40	250	60	1000
Citrus	30	270	60	350
Grapes	20	170	60	220
Mango	15	100	25	110
Papaya	50	90	25	130
Pineapple	50	185	55	350
Passion fruit	15	60	15	75

to withstand adverse conditions, helps in the development of a strong and healthy root system and increases the absorption and utilization of other nutrients (Sulladmath et al. 1984). To get optimum yield, different fruit plants differ in their nutrient (N, P_2O_5 and K_2O) requirement. For example, the available information on nutrients requirement of lemon to improve its yield and fruit quality is small as compared to oranges, however the Study of Koo (1963) showed that potassium requirement for lemon was much higher than that of orange and recommended rates of potassium fertilizers were 25 per cent higher than those for nitrogen, for optimum yield of lemon. The data presented in Table 1 showed that N, P_2O_5 and K_2O requirement of banana fruit was much higher than that of papaya and passion fruits. Drastically higher consumption of potassium (K_2O) was reported in case of banana fruit (1000 kg ha^{-1}). Citrus fruits also consume relatively higher amount of K_2O than that of grapes, mango and papaya fruits. Interestingly, citrus and pineapple need same amount of K_2O fertilizer with a yield difference of 20 t ha^{-1}.

Fruit quality is the degree of excellence or superiority is a combination of attributes, properties, or characteristics that give each commodity value in terms of its intended use (Geraldson 1985; Ramesh Kumar 2004). The relative importance given to a specific quality attribute varies in accordance with the commodity concerned and with the individual producer, consumer, and handler or market concerned with quality assessment. To producers, high yields, good appearance, ease of harvest, and the ability to withstand long-distance shipping to markets are important quality attributes (Koch and Mengal 1974; Mengal 1997). Appearance, firmness, and shelf-life are important from the point of view of wholesale and retail marketers. Consumers, on the other hand, judge the quality of fresh fruits on the basis of appearance at the time of initial purchase (Shamshiri and Usha 2004; Sipiora et al. 2005). Subsequent purchases depend upon the consumer's satisfaction in terms of flavor and quality of the edible part of fruits.

Potassium and physiological processes in fruit crops

In general, in addition to activation of more than 60 enzyme systems in fruits, K helps in photosynthesis, favors high energy status, maintains cell turgour, regulates opening of leaf stomata, promotes water uptake, regulates nutrients translocation in plant, favors carbohydrate transport, enhances N uptake, helps in protein synthesis and promotes starch synthesis.

Parameters to define fruit quality

Following are the important quality parameters in fruits which affect the economics of fruit production and nutrition value of fruits

Appearance quality factors

This parameter is very important from the marketing point of view to fetch higher price. It includes size, shape, color, gloss, and freedom from defects and decay. Defects can originate before harvest as a result of damage by insects, diseases, birds, hail, chemical injuries and various blemishes. Post-harvest defects may be morphological, physical, physiological, or pathological.

Textural quality factors

These include firmness, crispness, juiciness, mealiness, and toughness, depending on the commodity. Textural quality of horticultural crops is not only important for their eating and cooking quality but also for their shipping ability. Soft fruits cannot be shipped over long distances without substantial losses due to physical injuries. In many cases, the shipment of soft fruits necessitates that they be harvested at less than ideal maturity, from the flavor quality standpoint.

Flavour quality factors

These include sweetness, sourness (acidity), astringency, bitterness, aroma, and off-flavors. Flavor quality involves perception of the tastes and aromas of many compounds. An objective analytical determination of critical components must be coupled with subjective evaluations by a taste panel to yield useful and meaningful information about the flavor quality of fresh fruits and vegetables. This approach can be used to define a minimum level of acceptability. In order to assess consumer preference for the flavor of a given commodity, large-scale testing by a representative sample of consumers is required.

Nutritional quality factors

Nutritional quality factor includes fat, oil, arytenoids, flavonoids, sterols and antioxidants. Fresh fruits play a significant role in human nutrition, especially as sources of vitamins (Vitamin C, Vitamin A, Vitamin B, thiamine, niacin), minerals, and dietary fibre. Other constituents of fresh fruits that may lower the risk of cancer and other diseases include carotenoid, flavonoids, isoflavones, phytosterols, and other phytochemicals (phytonutrients).

Potassium and nutritional value of crops

The nutritional value of fruits refers to the content of certain constituents such as protein, oil or fat, starch, mineral components and vitamins. The contents of fiber as well as the energy content are widely used parameters in assessing the value of food stuff in the human diet (Tandon and Kemmler 1986). Potassium (K) has a significant influence on increasing many human-health related quality compounds in fruits (Usherwood 1985). The content of nutritive elements, like proteins or oils, is used in many countries as a basis for procurement systems and thus, is an economic factor. Studies with the N isotope N_{15} showed that plants well supplied with K were able to take up more N, and moreover convert the N more rapidly into protein. Nitrate in the plant is reduced first to amines and then incorporated into amino acids to ultimately form proteins. A small K supply restricts NO_3 transport and inhibits protein formation, leading to an accumulation of nitrate-N and soluble amino-N in the plant. K influences on quality can also be indirect as a result of its positive interaction with other nutrients (especially with nitrogen) and production practices (Usherwood 1985). Potassium also improves and citric and ascorbic acid (vitamin C) content in juice, while influences other juice characteristics, like the acid/sugar ratio and soluble solids content (Koo 1985). The effect of K on increasing vitamin C is related with the improved sugar metabolism in the plant under proper K nutrition (Mengel 1997)

Potassium and food appearance

An adequate supply of K promotes the formation of fruits through a more intensive and longer period of photosynthesis. In citrus, K nutrition positively influences the size of fruit, thickness of the rind and fruit color (Anonymous 1975; Lester et al. 2010). The improved yield is due, in part, to reduced fruit fall from the tree and larger fruit size. Physiological disorders of citrus fruits like plugging and creasing, are associated with high N and low K availability. Potassium deficiency resulting in small, thin-skinned fruit promotes fruit splitting, even though extra K will not always correct normal splitting in susceptible cultivars. Plants adequately supplied with K show fewer incidences of pests and diseases (Shamshiri and Usha 2004). Fissures, cracks and lesions observed on K deficient fruits and leaves not only offer easy access to invading pathogens but also are less appealing to potential consumers at the market.

Contribution of various workers in generation of information on quality parameters in different fruits is summarized in Table 2. Fruit size and peel colour are important fruit characteristics for fresh market, while for their processing, soluble solids, juice, pectin and essential oil content are important parameters which help during storage.

Table 2 Information available on quality parameters of fruits

Quality Parameter	Fruit	References
Fruit size	Citrus	Shamshiri and Usha 2004
	Grape	Wojcik 2005
	Banana	Kumar and Kumar 2007
	Litchi	Mitra 2009
	Mango	Wojcik 2005
	Guava	Zehler et al. 1981
Colour	Citrus	Shawky et al. 2004
	Grape	Usherwood 1985
	Apple	Tandon and Kemmler 1986
	Litchi	Tandon and Kemmler 1986
	Banana	Kumar and Kumar 2007
Soluble solids	Citrus	Tiwari et al. 1999
	Banana	Kumar and Kumar 2007
	Grape	Usherwood 1985
	Guava	Mitra 2009
	Mango	Wojcik 2005
	Papaya	Sulladhmath et al. 1984
	Pineapple	Stewart 1956
Acidity	Citrus	Shawky et al. 2004
	Grape	Usherwood 1985
	Papaya	Sulladhmath et al. 1984
	Guava	Zehler et al. 1981
	Mango	Wojcik 2005
	Pineapple	Stewart 1956
	Banana	Kumar et al. 2006
Soluble solids	Citrus	Shawky et al. 2004
	Guava	Zehler et al. 1981
	Aonla	Wojcik 2005
	Banana	Kumar and Kumar 2007
	Pineapple	Stewart 1956
	Papaya	Sulladhmath et al. 1984

Effect of foliar application of potassium on yield and quality of fruit crops

There are several potassium chemicals that can be used commercially in fruit orchards. Potassium nitrate and potassium sulphate can be applied as foliar sprays to increase the fruit yield and quality. The double salt sulphate of potash magnesia is widely used in areas where magnesium deficiency occurs. Using ammonium fertilizers as the nitrogen source can increase the uptake of K. An optimum level of K is most important in relation to external aspects of fruit quality (Embleton et al. 1973). Excessively high K levels result in large fruits with coarse, thick peel and poor colour. Moreover, early and intensive regreening will occur in such fruit plants (orchards). On the other hand too low K levels in fruit plants result in small fruits, which are rejected by the fresh fruit and export markets, in spite of their thin rinds and good colour. Potassium decreases the loss of fruit from creasing, splitting and the addition of auxins can further reduce these peel disorders. In citrus, K improved both the citric and ascorbic acid content of the juice, as well as other juice characteristics, like the acid/sugar ratio and soluble solids content. Vitamin C (commonly referred to as ascorbic acid) is perhaps the most popular vitamin.

Soil and foliar application of K has been shown to increase the level of ascorbic acid in banana, guava and papaya. Fruits crops receiving adequate K give a larger root yield with increased sugar content and consequently much larger sugar content in the fruits. The lower sugar content in fruits receiving inadequate K derives from reduced translocation of assimilates from the leaves into the storage organ due to restricted phloem loading.

Table 3 Effect of potassium fertilization on leaf K, yield and fruit size of 'Shamouti' orange

Treatment	1984	1985	1986	1987
Leaf K% (D. Wt.)				
-K	0.45	0.60	0.44	0.51
+K	0.64	0.85	0.67	0.87
Sign.	+	+	+	+
Yield (ton ha^{-1})				
-K	67	57	71	67
+K	77	54	86	72
Sign.	+	-	+	-
Fruit weight (g)				
-K	181	211	187	172
+K	193	256	197	222
Sign.	-	+	-	+

Source : Dasberg 1988, + Significant, - Not significant

The data presented in Table 3 depicted the effect of potassium fertilization on leaf K content, fruit yield and fruit size of Shamouti a variety of orange over a period of 4 years beginning from 1984 to 1987. From 1984 till 1987 a significant and positive increase in % leaf K concentration (on dry wt. basis) was observed with the application of K as compared to the control whereas fruit yield (t ha^{-1}) and fruit weight (g) showed a positive and significant increase with K application on alternate years. Potassium application increased the orange yield significantly in 1984 and 1986 as compared to control, whereas fruit weight was significantly higher in 1985 and 1987.

Fruit weight (kg), TSS (%), acidity (%) and ascorbic acid (mg 100 g^{-1} pulp) content increased with an increase in concentration of KCl and highest values for these were observed at foliar application of 2.0 percent KCl concentration as compared to control and 1.0 percent KCl concentration (Table 4). Fruit weight was significantly higher at 2.0 percent KCl concentration by 8.8 kg as compared to control whereas TSS (%) was significantly lower in control as compared to 1.0 percent and 2.0 percent KCl concentrations by 0.24 and 0.38 percent respectively. Similarly, acidity (%) was significantly higher in 1.0 percent and 2.0 percent KCl concentrations as compared to control by 0.042 and 0.030 percent respectively whereas a significant difference of 0.012 percent was also observed between 1.0 percent and 2.0 percent KCl concentrations. Ascorbic acid content at 2.0 percent KCl concentration was significantly greater than that for control and 1.0 percent KCl concentration by 4.7 and 2.5 mg 100 g^{-1} pulp respectively. Application of foliar K markedly improved several cantaloupe fruit quality parameters, despite sufficient soil test K levels (Koch and Mengal 1974; Usherwood 1985).

Table 4 Effect of foliar application of KCl on fruit weight and quality of Sardar guava

Treatments	Fruit Weight (kg)	TSS (%)	Acidity (%)	Ascorbic Acid (mg 100 g^{-1} pulp)
Control	133.0	11.28	0.296	237.7
1.0% KCl *	136.7	11.52	0.326	239.9
2.0% KCl	141.8	11.66	0.338	242.4
CD (P=0.05)	5.61	0.144	0.009	1.543

Source: Kundu et al. 2007; *Two sprays - May 10th and September 10th.

The experiments conducted at Bidhan Chandra Krishi Vishwavidyalya, Mohanpur, West Bengal indicated that increase in levels of applied K increased the yield of fruits varying from 13.8 to 35.7 percent in different fruits (Table 5). Similarly, the total sugar yield increased from 4.2 to 34.1 percent in different fruits.

Table 5 Effect of K application on yield and total sugar in different fruits

Fruit	Variety	Increase in applied K (g plant^{-1} yr^{-1})	Increase in fruit Weight (g)	Per cent Increase	Increase in total Sugar (%)	Per cent increase
Mango	Fazli	150 to 1000	595 -748	25.7	12.0-12.5	4.2
Banana	Giant	120 to 240	117-139	18.8	14.6-16.7	14.4
Pine Apple	Kew	200 to 600 **	1400-1900	35.7	12.8-15.2	18.7
Litchi	Bombai	200 to 600	18.1-20.6	13.8	13.9-15.8	13.7
Guava	Sardar	130 to 260	152-176	15.8	7.93-8.72	14.3
Papaya	Ranchi	200 to 600**	1420-1640	15.3	5.07-6.80	34.1
Mandarin orange	-	200 to 600	84-107	27.4	8.30-9.80	18.1

Source: Mitra 2009 ** kg ha^{-1}

The maximum increase in fruit weight (35.7 %) was observed in pine apple (Kew var.) when the rate of K application was increased from 200 to 600 kg ha^{-1} yr^{-1}. Correspondingly, an increase of 18.7 percent in total sugar was also observed for the same fruit. The highest increase in fruit size of pine apple was followed by Mandarin orange where an increase of 27.4 percent was observed when the rate of K application was increased from 200 to 600 g plant^{-1} yr^{-1} with a corresponding increase of 18.1 percent in total sugars. In mango (var. Fazli) when the rate of K application was increased from 150 to 1000 g plant^{-1} yr^{-1} there was a corresponding increase of 25.7 percent and 4.2 percent in fruit weight and total sugars respectively. An increase of 18.8 and 14.4 percent respectively, was observed for fruit weight and total sugar in banana (Giant var.) for a 120 g increase in K per plant when the rate of K application was increased from 120 to 240 g plant^{-1} yr^{-1}. Fruit weight in guava (Sardar var.) increased by 15.8 percent, while a corresponding increase of 14.3 percent was also observed for the total sugar when the rate of K application was increased from 130 to 260 g plant^{-1} yr^{-1}. In Papaya, with an increase of about 400 g K plant^{-1} yr^{-1} there was an increase of 15.3 and 34.1 percent in fruit weight and total sugar respectively. Lowest increase in fruit weight (13.8%) with a corresponding increase of 13.7 percent in total sugars was observed in Litchi (Bombai var.) although the rate of K application was increased from 200 to 600 g plant^{-1} yr^{-1}.

The effect of sulphate of potash (SOP) on yield, quality and post-harvest life of eypoovan banana has been observed (Table 6). Increased concentrations of potassium sulphate improved the bunch weight, TSS, sugar to acid ratio and self-life of banana. With an application of 1.5 percent in SOP, bunch weight increased significantly by 4.47 kg as compared to control treatment. Significant increases of 1.1 and 1.64 kg respectively in bunch weights were observed as the SOP concentration was gradually increased by 0.5 percent upto 1.5 percent. On the other hand, TSS (%) at SOP concentrations of 1.0 and 1.5 percent was similar but significantly higher than control by 4.5 percent. A decrease in acidity (%) was observed in eypoovan banana with an increase in SOP concentration and acidity at 1.0 and 1.5 percent concentrations of SOP was significantly lower than control by 0.17 percent. A rapid increase in sugar to acid ratio (sugar:acid) with increasing SOP concentration was observed with highest ratio being observed at 1.5 percent SOP concentration which was significantly higher than control by 46.7 whereas it was significantly higher at 0.5 and 1.0 percent SOP concentrations by 20.9 and 33.4 respectively as compared to control. Shelf life (days) was similar for 0.5 and 1.0 percent SOP concentrations (7.8 days) but it was significantly higher than for control by 1.3 days. Similarly, shelf life was more at 1.5 percent SOP concentration as compared to control by 2.2 days.

Table 6 Sulphate of potash (SOP) foliar spray effects on yield, quality and post-harvest life of eypoovan banana

Treatments	Bunch weight (kg)	TSS (5)	Acidity (%)	Sugar:Acid ratio	Shelf life (Days)
Control	10.80	24.4	0.40	50.9	6.5
0.5% SOP *	11.53	27.9	0.30	71.8	7.8
1.0% SOP	12.63	28.9	0.23	84.3	7.8
1,5% SOP	14.27	28.9	0.23	97.6	8.7
CD (P=0.05)	1.02	2.06	0.024	6.72	0.98

Source: Kumar and Kumar 2007; * Sprayed twice, initially after the opening of last hand (7th month after planting) and 30 days later

In banana, potassium improves fruit weight and number of fruits per bunch, and increases the content of total soluble solids, sugars and starch (Table 7) (Bhargava et al. 1993).

Table 7 Effect of K levels on yield and quality of bananas

K_2O (g pl^{-1})	Bunch weight (kg)		Yield (t ha^{-1})		Total sugar (%)		TSS (%)		Acidity (%)	
	P	R	P	R	P	R	P	R	P	R
0	12.0	12.1	30.0	30.2	11.0	11.9	15.9	16.0	0.59	0.59
240	13.4	14.2	33.5	35.5	12.6	12.6	16.5	16.4	0.55	0.55
480	15.2	15.3	38.0	38.2	13.1	13.1	17.0	17.0	0.53	0.52

Source: Bhargava et al. 1993. P = Plant, R=Ratoon

Effect of Potassium on storage/shelf life of fruit crops

The effects of K on shelf life are predominantly favorable, both through slowing senescence and through a decrease of numerous physiological diseases. Potassium increases firmness and strengthens the skin of fruits, thus they are not damaged easily during transport, resist decay for a longer period and stay fresh longer.

Increased K application reduces the post harvest moisture loss by increasing the weight of the harvested organs and maintaining tissue integrity. Potassium also reduce the incidence of some storage fungal diseases that may cause considerable losses, because fruits, tubers or roots showing even minor damage must be discarded before marketing. Storage compounds accumulating in the harvested organ during growth and maturation are consumed in the course of metabolic activitites during storage. Respiration includes the oxidative breakdown of sugars, starch and organic acids into carbon dioxide and water, with the concurrent production of energy, heat and intermediary compounds to be used in biochemical reactions. With a shortage of K, the rate of respiration is increased and more energy is required for this function, thus fruits do not last long in storage.

The direct relationship between K and storage life of fruits has been reported by various workers (Table 8).

Table 8 Relation of K and storage life of fruits

Fruit	Effect	References
Mango	+	Wojcik 2005
Citrus	+	Shamshiri and Usha 2004
Pineapple	+	Stewart 1956
Grape	+	Wojcik 2005
Banana	+	Kumar et al. 2007

+ Positive effect

Adequate K nutrition has been associated with increased shelf life, and shipping quality of many horticultural crops (Kumar et al. 2006). Fruits from trees sprayed with K were firmer and better quality than the control fruit during the storage period (Robertson et al. 1990). K application on Kaki fruit increased fruit firmness (El-Fatah et al. 2008) thus improving storage period. Potassium enhanced storage and shipping quality of bananas and many other crops, and also extends their shelf life (Bhargava et al. 1993; Geraldson 1985; Koo 1985; Mengel 1997; Usherwood 1985; Von Uexkll 1985). Quality of citrus fruits during storage is also influenced by K nutrition of the tree. The incidence of stem-end rot and green mold is reduced as K fertilization rate is increased, therefore fruit loss during transport is reduced and shelf life in the supermarket is increased (Koo 1985). A low potassium nutrition results in thin and fragile bunches with shorter shelf life (Von Uexkll 1985).

Stewart (1956) studied the post harvest behavior of pineapple as affected by different sources of potassium (Table 9) at harvest and at 28 days of storage and observed that at harvest maximum TSS (15.5%) was observed with KCl while the minimum value for TSS (15.1%) was observed when K_2SO_4 was used as a source of K. At 28 days of storage, TSS was highest (15.5%) when a mixture of KCl+ K_2SO_4 was used and lowest (14.7) when KCl was used as a source of K. Similar trends were observed for acidity at harvest as well as at 28 days of storage. At harvest, maximum acidity (0.55%) was observed with KCl while the minimum value for acidity (0.50%) was observed when K_2SO_4 was used as a source of K, at 28 days of harvest, highest (0.67%) and lowest (0.54%) values of acidity were observed when KCl and K_2SO_4 were used as sources of K respectively. At harvest, firmness was maximum (13.9) when a mixture of KCl+ K_2SO_4 was used and minimum (11.7) when KCl was used as a source of K while at 28 days of storage maximum (9.6) firmness was observed while using K_2SO_4 while minimum (8.0) was observed using a mixture of KCl+ K_2SO_4. Post-harvest characteristics of fruits were more affected by K rates than by K sources.

Table 9 Post-harvest behaviour of pineapple affected by sources of potassium

Source of K	TSS° Brix	Acidity (%)	Firmness
At Harvest			
KCl	15.5	0.55	11.7
K_2SO_4	15.1	0.50	12.7
KCl+K_2SO_4	15.4	0.53	13.9
At 28 days of Storage			
KCl	14.7	0.67	8.5
K_2SO_4	15.4	0.54	9.6
KCl+K_2SO_4	15.5	0.59	8.0

Source: Stewart 1956

The scientific literature also contains examples of studies with conflicting results of the beneficial effects of K fertilization on fruit quality. These conflicting results can be explained by taking into consideration the differences in modes of fertilization i.e. soil applied (dry) vs. foliar application, fertigation or hydroponic applied, differences in forms of K fertilizer e.g. glycine-complexed K, versus K_2SO_4, KCl, or KNO_3 from K fertilization, timing of application with regard to crop phenology or soil chemical and physical properties such as pH, calcium and magnesium contents, and textures (sandy vs. clay). These properties are known to influence soil nutrient availability and plant uptake, and soil fertilizer K additions under such conditions may have little effect on uptake, yield and fruit quality (Mengal 1997). In a number of studies involving several fruiting crops e.g. mango and citrus where soil-applied fertilizer K was compared to foliar K applications, the latter approach consistently resulted in improved fruit quality attributes during processing whereas the former approach generally had little or no effects (Marshner et al. 1996; Perrenud 1990). Furthermore, in studies where several fertilizer K salts were evaluated, fruit quality improvements during storage appeared to depend on timing of application as well as fertilizer K formulation. For instance, when mid- to-late season soil or foliar K applications were made using KNO_3 there were little or no improvements in fruit quality or human nutritional quality attributes and in some instances, these attributes were actually inferior compared to fruit from control plots (Lester et al. 2010).

Conclusions

Potassium is important in optimizing both crop yield and economic quality of fruit crops. A balanced nutrition allows K to contribute its best towards higher yield, quality and profitability. Potassium enhances the quality parameters of fruits thus helping consumers to eat good quality and nutritious fruits and farmers to get more profit.

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