CHAPTER 1: **INTRODUCTION**

1.1 Introduction

Rice (*Oryza sativa*.L) is one of the major cereal crops in Iraq and critical for food security. Farmers grow rice in most districts of Najaf and Al Diwaniyah provinces and cultivate rice in 70% of the potential area. The productivity of the most common Iraqi rice cultivar, Amber33, is 2.9 t/ha (Ministry of Planning 2007) which is low compared to an average production of 4.2 – 5 t/ha among major rice-producing countries (Larijani 2006; Mutert and Fairhurst 2002).

Iraq currently has 125,000 ha of land under rice cultivation, of which 75,000 ha have irrigation facilities. About 400,000 metric tons of rice are produced. The Iraqi people consume 900,000 tonnes of milled rice with provisioning cards, and more than 2 million tons of milled rice in total. Rice is imported from Thailand, Vietnam, India, and Pakistan to satisfy Iraq's demand (Hameed 2005; Hameed *et al.* 2008).

Iraqi rice farmers mostly cultivate rice according to the cultural practices inherited from their parents. They use a large amount of seed (about 160 kg/ha). Transplanting is not common in Iraq. If farmers use transplanting methods, they transplant seedlings at a distance of 25×20 cm within and between lines, respectively. They do not utilize organic matter (manure or compost), but depend on chemical fertilisers such as urea and diammonium phosphates (DAP) (Al-Zubaidi 2004). There is no addition of potassium (K) fertiliser and substantial removal of straw from the field, potentially resulting in continuing soil K depletion and causing rapid expansion of K deficient areas and locally significant responses of crop yield to K fertilisation.

Farmers generally grow the aromatic local cultivar Amber33 because it is preferred by Iraqi consumers, having become popular during the blockade. However Amber33 has a lodging problem, which can affect yields and quality. Farmers can have entire fields lodge and it is very difficult to harvest rice that is on the ground. Lodging of rice in Iraq reduces production by 25 – 30% and may be related to the agronomic practice of supplying high nitrogen (N) and phosphorus (P) nutrition in the absence of applied K. It is proposed that improving K nutrition and better balancing K applications with N and other essential nutrients may increase Amber33 rice yields. To test this proposition, competition for uptake by rice of K with other nutrients and the effects of K on growth and yield of rice need to be investigated as well as the effects of K on the rice root system.

It is hypothesised that improvements in crop and fertiliser management could rapidly increase rice yields. It is further proposed that increasing Amber33 rice yields may be related to improved K nutrition and better balance of K applications with N and other essential soil nutrients. In addition, due to the inherently high salinity in many Iraqi rice-growing regions (Rechardson *et al.* 2005), the interaction of K nutrition with sodium (Na) and salinity stress may also affect yields and needs to be investigated under controlled conditions to ensure that yield and fragrance of Amber33 are increased. Therefore competition in K uptake by rice from Na will need to be investigated.

It is possible that the soils need more K when growing this specific cultivar (Amber33) of rice. The Iraqi people are unlikely to change the rice they eat because the aroma this particular cultivar produces is so desirable. Since 1991, farmers found they could provide food security for the people if they also cultivated wheat (*Triticum aestivum* L.) after rice (Hameed 2006); however, this system may further exhaust K reserves in rice soils in Iraq.

The propositions being explored in this thesis suggest that improved management of K is now very important for sustaining or increasing crop yield in Iraq. Proper K management requires a thorough understanding of soil K behaviour (Al-Zubaidi 2004) and of the various K inputs and outputs of cropping systems. It is well known that the availability of K to plants does not only depend on the size of the available pool in soil, but also on the transport of K from soil solution to the root zone and from the root zone into plant roots.

The aims of the research described here were firstly, the evaluation of the K fertiliser rate and rice cultivar on rice lodging under high N conditions, and secondly, an assessment of the effect of salinity and K on rice growth parameters. Finally, estimation of the effect of K on rice root distribution. In order to achieve these objectives a series of studies were conducted.

A non-sodic non-saline Black Vertosol was used in all pot experiments and water was managed using a flooded regime with 4 – 5 cm water layer at the top. The soil was chosen to match typical Iraqi rice production soils in that it is a cracking clay soil with low available K status. Using a non-saline soil meant that salinity treatments could be imposed by adding salt.

The basic structure of this thesis is presented below; the results of the study are discussed in each chapter and then brought together in a general summary along with suggested further studies.

The review of literature (Chapter 2) discusses rice in relation to K, the function of K in plants, K availability and interaction with other nutrients, and factors affecting K fixation in soils. The major limitations of rice production such as lodging and salinity are examined. Evidence from review of literature suggested that K may affect both salinity tolerance and resistance to lodging under high N and P fertilized conditions and the therefore the first study undertaken addressed this hypothesis.

Chapters 3 and 4 demonstrated positive effects of K application on stem strength and lodging incidence and an ability to reduce the damage of high salinity on rice production. Within these chapters evidence was collected that implicated root growth as the main mechanism through which positive effects of K application are mediated. As a consequence, further detailed investigations of the effect of K on root growth of rice were commenced and outlined in Chapter 5.

In Chapter 6, field experiments were established on a clay loam soil at three sites in Iraq to investigate whether the beneficial effects of K in pot and glasshouse studies would be expressed under field conditions with stresses such as high temperature and low K prevalent. Positive effects were also observed in the field in Iraq leading to a final summary chapter that suggests further research avenues for K nutrition of rice (Chapter 7).

CHAPTER 2: **LITERATURE REVIEW**

2.1 Introduction

This chapter reviews rice production and the role of potassium (K) in rice nutrition, lodging, carbohydrate production, root distribution and focuses on critical soil values of K for optimal rice production. The factors affecting soil solution K such as salinity, nutrient competition and fixation, critical values and plant uptake of K from the soil solution will also be discussed. An overview of foliar application of K to cereals, and the effects of this application on rice production will be presented, as well as the factors affecting K availability to plants.

2.2 Rice

Rice (*Oryza sativa* L.), is an important food crop worldwide whose demand is projected to increase with population growth (Brohi *et al.*1998; Kebbeh and Miezan 2003; Xie *et al.* 2007). The average yield of rice is estimated at 3.5 t/ha (Dobermann and Cassman 1996; Fageria *et al.* 1997; Mears 1978; Nanda and Agrawal 2006; Szczerba *et al.* 2008; Zeng *et al.* 2002). More than 90% of the rice grown globally comes from Asia, where the crop is a significant staple accounting for 30 – 75% of the daily calorie intake of the population (Dobermann and Cassman 1996). At present, half of the world's population depends on rice production for survival, supplying nearly 50% of that demographics energy needs (Mears 1978; Yang and Hwa 2008). Rice productivity does not only vary from one country to another, but also within a country, and this difference reflects the diverse agro-ecological zones and production systems used (Van Tran 1998). At present, China and

India currently produce more than 50% of the total world rice crop, while other significant rice-producing countries include Indonesia, Bangladesh, Vietnam, Thailand and Japan.

Rice is an annual cereal crop which belongs to the grass family *Poaceae* (*Gramineae)*. Rice cultivars vary in size, length, shape, angle of the primary branches, and in panicle weight and density all of which affect yield potential (Chang and Bardenas 1965). Rice is a crop that can be grown under diverse conditions worldwide, including both dry and wetland conditions (Fageria 2001; Hoa 2003). Rice cultivars have been adapted to a wide range of soil types, but fine-textured (clayey) soils are generally the most suitable because of their high water–holding capacity. Rice crops can also adapt to soil acidity ranging from acid soils of pH around 5.0 to alkaline soils with a pH of 8.3. Rice has a medium tolerance to soil salinity with an upper limit approaching 3 dS/m (Mass and Hoffman 1977), with production potentially falling to less than 50% of optimum yield when soil salinity exceeds 6 – 10 dS/m (Fageria and Zimmermann 1996; Mass and Hoffman 1977; Nanda and Agrawal 2006). Rice yields are strongly influenced by climatic conditions, cultivar choice and management practices (Xie *et al.* 2007). Deficiencies of essential nutrients such as N, P and K and microelements also affect the potential yield (Doberman and Witt 2004).

Rice straw provides a very important source of organic matter (OM) to improve soil productivity (Dobermann and Fairhurst 2002). Rice straw contains more than 20% ash, significantly higher than wheat and barley at 5 – 10% (Byous *et al.* 2004). According to Kuangfei *et al.* (1999), rice straw contains 0 – 7% N and 1.9% K. In addition, Dobermann and Fairhurst (2000, 2002) reported that about 30 – 35% N and 80 – 85% K taken up by rice remains in vegetative plant parts at maturity. Most of these nutrients are available to a subsequent crop when the straw is left in the field (Byous *et al.* 2004). Depletion in soil K occurs when the straw is removed (Dobermann and Fairhurst 2002), and this leads to K-induced reductions in crop yield (Byous *et al.* 2004).

The fertilisers typically applied in rice production are nitrogen (N), phosphorus (P) and K which have the ability to significantly increase yield (Husnain *et al.* 2010). Next to N, crops absorb K in greater amount than any other nutrient (Frank 2000). In addition to N, P and K, rice plants also require large amounts of silicon (Si) (Husnain *et al.* 2010). In a rice yield of 5 t/ha between 75 – 120 kg N/ha, 20 – 25 kg P/ha, 23 – 275 kg K/ha and 230 – 470 kg Si/ha are removed at harvest (Cassman *et al.* 1996; Dobermann *et al.* 1996a, b; Savant *et al.* 1997). Potassium has received less attention from rice farmers in Iraq who tend to focus on N and P. Maintaining a good level of these nutrients in the soil is important for the improvement of rice productivity.

2.3 Potassium

Potassium is an essential cation nutrient due to its important regulatory role for plant growth. In most soils, K is present in higher concentrations than N and P (Prasad and Power 1997). The K content in soils is variable, and dependant on the parent material that formed the different minerals and clays (Frank 2000). Unlike N and P, K in soils is not associated with the level of OM (Frank 2000). The earth's crust contains about 1.9% K, and the surface (0-10 cm) soil content of K may vary from a ~200 kg/ha in sandy soils to 50,000 kg/ha in heavy clay soils which are rich in 2:1 clay minerals (Prasad and Power

1997). The total K in the soil varies from 0.3% to more than 2.5%, depending on soil type, and 90 – 98 % of soil K is in unavailable forms (Frank 2000).

2.3.1 Potassium function in plants

Potassium is essential to plant growth (Gierth and Maser 2007), although it does not become a part of the plant's chemical structure. The nutrient is particularly vital to biochemical and physiological processes: activation enzymes like nitrate reductase, catalysis of proteins, moderation of salt-water balance, and storage and release of energy are all dependant on K. Potassium also plays a key role in mediating the processes of cell division, photosynthesis and carbohydrate formation, ATP synthesis and sugar transfer (Chen *et al.* 1980; Chrispeels *et al.* 1999; Dobermann and Fairhurst 2000; Fageria *et al.* 1997; Havlin *et al*. 2005; Kumar 2009; Imas and Magen 2000; Mengel and Kirkby 1982; Tisdale *et al*. 1993; Wolf 1999). More recent research also identifies a key role in resistance to biotic and abiotic stress, particularly diseases and pests, and frost/heat tolerance (Romheld and Kirkby 2010). Potassium ions also control the process of opening and closing stomata, water uptake, the length and radius of the roots and overall root growth, including root hair density (Din *et al.* 2001; Kumar 2009; Surendran 2005). Potassium has also been reported to increase the strength and thickness of stems as well as facilitate increased N uptake by plants (Aide and Picker 1996).

2.3.2 Potassium concentration in plant tissue

Plant tissue concentration of K is known to increase with the amount of exchangeable K^+ maintained in the soil solution, and this ion availability impacts on the yield of rice. Potassium uptake is constantly active and hence luxury uptake of K is often observed in most species (Marschner 1996). Aide and Picker (1996) found that K application rate of 84 kg K/ha increased K concentration in plant tissue from 0.94 to 1.03%. However the relationship between K application and K tissue concentration is not necessarily straight forward. Aide and Picker (1996) found that K concentration in plant tissue when supplied at a rate of 28 kg K/ha was similar to that at a K rate of 84 kg/ha and attributed that to the extremely low initial K level in the soil. The concentration of K in the grain is generally low (Barber 1984) when compared to the 80% of K that remains in straw (Yusob *et al.* 2007). Detailed discussion of K uptake regulation is contained in Section 2.3.9.

2.3.3 Sources of potassium in soil

The main sources of K in soil for plants include: (i) weathering of K-bearing minerals (i.e. feldspar and mica contain more K), which differ in structure and K fixation as well as release patterns; (ii) exchangeable K on the soil colloidal surfaces especially after replacement by other cations such as Ca^{2+}, Mg^{2+} ions in alkaline soil and H^+ ions in acid soil; (iii) K-based mineral fertilisers, mainly muriate of potash KCl and sulphate of potash K_2SO_4 and organic resources both of plant and animal origin. The concentration of K in soil solution at any given time will depend on how much is released from the various sources into soil solution or withdrawn from the soil solution and the rate at which those processes occur (Frank 2000; Havlin *et al.* 2005; Mengel *et al.* 2001).

2.3.4 Factors affecting potassium availability in soil

Potassium is the seventh most abundant element in the earth's crust, however only 1 – 2 % of total K is available to plants, 1 – 10 % is exchangeable and the balance is fixed with other minerals and not available for the plant (Romheld and Kirkby 2010). Based on the availability of K in soil, K fractions are usually classified into: (i) mineral (ii) fixed (iii) exchangeable and (iv) soluble K and are in dynamic equilibrium in soil (Figure 2.1). Potassium can be transferred from both available and exchangeable forms to unavailable forms comprising 90% of the total K in soil. The availability of soil K depends mainly on the types and amounts of soil minerals present. If clays such as vermiculites or highly charged montmorillonite are present, K may be fixed in interlayer region of these 2:1 clays, and be slowly released as the minerals are subjected to weathering conditions or to wetting and drying cycles (Bahmaniar and Ranjbar 2007b; Huang 2005; McLaren and Cameron 1996; Mengel 1985; Mengel *et al.* 2001).

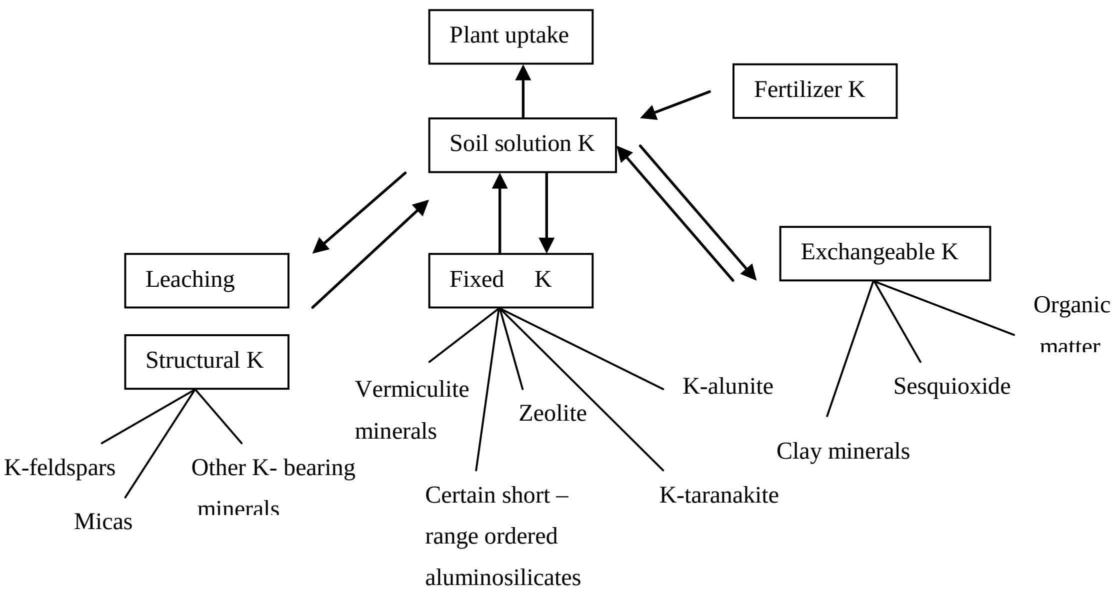


Figure 2.1 Interrelationships of various forms of soil K.
Source: Sparks and Huang (1985).

Bijay-Singh *et al.* (2004) and Regmi *et al.* (2002) noted that an available soil K of 0.1 $cmol_c/kg$ indicated potential K deficiency for rice, irrespective of the actual K content. Exchangeable soil K^+ will be depleted if K is not added externally to the system, declining annually until replenishment from mineral sources in the soil or using K fertilisers reaches steady levels of exchangeable K. Non-exchangeable K slowly transfers to exchangeable K, while exchangeable K rapidly moves to soil solution K (Brady and Weil 2002). For K-fixing soils, as solution K falls, release of K from interlayer spaces is accelerated, but in depleted soils applied K fertilisers are rapidly fixed back into these interlayer spaces (Hoa *et al.* 1998; Jalali and Kolahchi 2006; Mehdi *et al.* 2001; Ogaard and Krogstad 2005).

Potassium supply capacity of the soil decreases annually without K application, which can affect plant growth. When exchangeable K in soil falls below 40 to 80 mg/kg, K deficiency symptoms appear in rice plants between the panicle and heading stages (Dorji and Uden 2003; Espinosa 2002; Hoa *et al.* 1998; Slaton *et al.* 2004). The range in critical extractable values occurs because of variation in CEC, pH and Ca and Mg concentrations in the soil.

Potassium in solution is more mobile than $H_2PO_4^-$ but less than mobile than NO_3^- (Huang 2005). Moreover, the rate of K loss in soil is significant, and K leaching is associated with coarser textured soils (Spark and Huang 1985; Tisdale *et al.* 1993; Wolf 1999).

The loss of K^+ by leaching can be associated with the nitrification processes through movement of K as the positive counterion to nitrate (Brady and Weil 2002; Pieri 1992). This is a consequence of ammonification and nitrification processes, where NO_3^- and H^+ are produced illustrated by:

$$\text{Proteins, nucleic acids} \rightarrow NH_4^+ + OH^- \ \text{……..Ammonification}$$

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+ \text{................Nitrification}$$

Exchangeable cations such as Ca^{2+}, Mg^{2+} and K^+ can be displaced by H^+. Secondly, NO_3^- production will lead to an increase in the concentration of anions in soil solution, which must be balanced by cations (White 2006). In limed soil, Ca^{2+} and Mg^{2+} can be replaced by K^+ which will reduce K leaching. In acid soils, exchange sites are saturated by Al^{3+}, so K^+ can be readily lost to the system. However, liming an acid soil may reduce the loss of K by leaching, and the effect of complementary ions can reduce K losses (Brady and Weil 2002).

Soil solution K^+ in arable soils is controlled by factors such as the nature and type of the crop, soil structure, fertility of soil, soil moisture supply, and the stage of crop growth. The range of optimum K^+ concentrations in soil solution varies among soils. It usually amounts to 1 – 60 kg/ha, whereas K activity in soil solution is significantly affected by activity of Mg^{2+} and Ca^{2+}, and the relationship between K^+ on the sites with negative charges, such as mineral and organic colloids (Barber 1984; Jalali and Kolahchi 2006; Jalali and Zarabi 2006; McLaren and Cameron 1996; Mengel 1985; Mengel 2007; Sharpley 1989; Tisdale *et al.* 1993). Beckett (1964) suggested that exchangeable K is held by two distinct mechanisms, general charge force fields and sites offering specific binding force for K, but not for Ca and Mg. The reaction rate between the soil solution and exchangeable phases of soil K depends mainly on the type of clay mineral present (Sparks 2001). However, the rate at which mineral K is slowly available to the plants depends on the degree of soil weathering (Sparks and Huang 1985).

2.3.5 Diffuse double layer

The diffuse double layer (DDL) occurs at the interface between the surface of clay minerals and the soil solution and is comprised of the usually negative charge of the surface of clay mineral and soil soluble cations. When the DDL is dominated by monovalent ions such as Na^+, the thickness of the layer is larger leading to a change in the nutrient ratios on the exchange surface. The separation of clay particles increases with increasing DDL thickness. DDL will be smaller with the presence of divalent ions such as Ca^{2+} and Mg^{2+} and a dilute solution where it flocculates the clay particles and increases water movement and hydraulic conductivity (Clark *et al.* 2000). While roots of plant are negatively charged, they are surrounded by DDLs. These conditions may affect the K^+ ions uptake, which will be limited by the amount of K ions in the layer.

2.3.6 Cation exchange capacity

Cation exchange capacity (CEC) shows the ability of soil to hold and provide the nutrient cations of Ca, Mg and K for the plant (Mengel *et al.* 2001). The uptake and availability of K can be affected by the balance of these ions. Cation exchange capacity is a helpful indicator for soil fertility (Singer and Munns 1996). The CEC associated with clay and organic matter increases with pH, strengthening the attraction of K for the colloid surface as pH rises (Wolf 1999). Barber (1984) indicated that CEC can influence K uptake especially if the dissociation of fixed-K declines with an increase in CEC. Also, the ability of cation to replace another cation is increased by raising the concentration and activity of these cations, which can be represented by the following equation:

$a = f \times c$ where: a= activity, f= activity coefficient, c=concentration.

According to Dobermann and Fairhurst (2000), the percentage of K saturation of total CEC is very important indicator for soil K supply, and suggested that K saturation percentages of < 1.5, 1.5 – 2.5%, and > 3.5% correspond to a low, medium and high status respectively. These ranges are related to K fertiliser response with low saturation indicating regular responses to K application. Furthermore, a soil Ca/Mg: K ratio > 100 may indicate that soil K availability is low to crops (Bijay-Singh *et al.* 2004). The assumption behind these ranges is that K is the most limiting factor in crop growth.

2.3.7 Quantity/ Intensity (Q/I) relationships

Quantity/ Intensity (Q/I) concept is generally used to investigate the status of soil K (Sparks and Liebhardt 1981). Availability of K to plants depends on its intensity (I) in the soil solution, quantity (Q), and renewal rate in the soil (Zhang *et al.* 2011). The equilibrium K activity ratio (AR^{k}_{e}) value is a measure of availability, or intensity, of available K in soil as described in the following equation:

$$\mathrm{ARk} = \frac{\mathrm{aK}}{\sqrt{\mathrm{aCa} + \mathrm{aMg}}}$$

Where (AR^{k}) activity ratio for K (or the intensity (I) factor), and (aK), (aCa) and (aMg) are the activities of K, Ca and Mg, respectively in the equilibrium solution in mol/L (Idigbor *et al*. 2009; Sparks and Liebhardt 1982; Zhang *et al.* 2011).

Q/I relationships are useful in polycationic systems as a relative index of soil K availability and allow for the assessment of K release from non-exchangeable to solution forms (Evangelou, *et al.* 1994). These relationships strongly suggest that the energy of exchange is governed by K-(Ca+Mg) interactions in the soil solution. Potassium activity is also affected by the difference in electrical potential across the diffuse double layer (DDL) which surrounds the exchange complex (Sparks 2000).

The K buffering capacity (PBC) is a measure of the ability of soils to maintain the intensity of K^+ in solution. A low PBC indicates that AR^K, or the intensity of K in the soil solution, and consequently availability of K to plants will drop quickly when the soils are cultivated or cropped (Idigbor *et al.* 2009). The AR^K increases following K fertiliser addition. This increase varies between soil types based on the differences in CEC values and original exchangeable K status. High CEC soils have smaller increases in AR^K whilst, low CEC soils have larger increases in AR^K (Al-Azawi and Guppy 2010). Furthermore, AR^K is negatively correlated with clay contents (r = -0.59), indicating that soils with higher clay contents usually have low AR^K values (Idigbor *et al*. 2009).

2.3.8 Factors affecting potassium fixation in soils

Potassium availability is influenced by K fixation (Sparks 2000). Fixed K can account for approximately 4 – 18% of applied K but remains an important K source in many soils (Jalali and Kolahchi 2006). Potassium ions can be fixed in 2:1 clay minerals such as illite chiefly between the silicate layers (Dobermann and Fairhurst 2000; Sparks and Huanng 1985). These clay minerals release and adsorb K more than other clay minerals (e.g. 2:1:1 oxide and 1:1 allophane) (Nursyamsi *et al.* 2008). Non-hydrated K^+ ions can fit within di-trigonal holes of the silicate clay minerals, which can lead to K fixation (Barber 1984). Therefore, the fixation or release of K^+ depends on the ability of these minerals to expand

and shrink under wet and dry conditions (Jury and Horton 2004; Khaled and Stucki 1991; McLaren and Cameron 1996; Mengel 1985; Tisdale *et al.* 1993).

Tisdale *et al.* (1993) the adsorption sites of 2:1 clay minerals such as illite, vermiculite and chlorite are usually classified into three exchange positions: planar (p), edge (e) and inner (i) (Tisdale *et al.* 1993). It is believed that the K^+ ions in the plane and at the edge of the sites are mostly used by plants (Jalali and Kolahchi 2006). According to Rodriguez and Rowell (2005), edge sites can also release exchangeable K; however, the release of non-exchangeable K is blocked when NH_4^+ reaches the wedge sites due to its similar ionic size (0.54 nm). Notwithstanding, more K is released when Ca^{2+} reaches these sites due to its greater size (0.96 nm), resulting in expanding interlayer spaces.

2.3.9 Potassium interaction with other nutrients

2.3.9.1 Potassium-sodium interaction

Both K and sodium (Na^+) are alkali cations whose demand and uptake mechanisms can differ greatly among plant species. Most plants exhibit high selectivity in K^+ uptake and accumulate more K^+ ions in their cells than Na^+ ions (Horie *et al.* 2007). However the presence of high concentration of Na^+ ions in the soil solution can antagonise the uptake of K and impair the function of essential enzymes (Bar-Tal *et al.* 1991; Horie *et al.* 2007). The concentration of Na^+ in shoots of rice has been shown to increase with increasing Na^+ concentration in root environment, while the concentration of K^+ decreases (Heenan *et al*. 1988). Sodium concentration affects the K:Na ratio. High soil K^+ reduces the uptake of surplus Na^+ in rice under flooded conditions (Cakmak 2005). High K uptake, particularly at panicle initiation, moderates the adverse effect of Na^+ uptake (Asch *et al.* 1999). Due to higher translocation of root K, the ratio of K to Na is 50 in cereal crop shoots (Dijkshoorn *et al.* 1974). However, in the presence of Na^+, significant uptake of Na^+ into the shoots follows restrictions in K supply (Elzam 1971 in Dijkshoorn *et al.* 1974). Although Na can substitute K in some nonspecific functions, such as control of turgor pressure, it cannot substitute for K in specific functions, including enzyme activation (Dobermann and Fairhurst 2000). High levels of K^+ reduce the uptake of Na^+, Mg^{2+} and Ca^{2+} in rice plants but have no influence on the uptake of NH_4^+-N in paddy soils under reducing conditions (Mengel *et al.* 1976). For example, the concentration of Na^+ decreased from 585 to 561, and to 429 mmol/kg in shoots and from 420 to 399, and to 260 mmol/kg in straw at EC 1.7, 6.0, and 12 dS/m, respectively, when K was applied at a rate of 50 mg K/kg soil plus 0.5% K_2SO_4 via foliar application (Din *et al.* 2001).

2.3.9.2 **Potassium-nitrogen interaction**

A high N content in a rice leaf enhances both the rate of photosynthesis and radiation use efficiency (Hasegawa and Horie 1996). However, high N applications may increase the number of sterile spikelets and thus, decrease the number of grains (Bahmaniar and Ranjbar 2007b).

There appears to be a synergistic relationship between N availability and K uptake. Barber (1984) reported that K uptake increases with increasing N fertilisation.

Brohi *et al*. (2000) reported that application of K at 66 kg/ha increased K levels from a control of 0.20% to 0.34% after applied K, and decreased the percentage of N in straw from 0.29% without K to 0.27%, but had no effect on N in the rice grain. However, when the concentration of external K is less than 1mM, the transport activity of K can be reduced by the presence of (NH_4^+) ions (Szczerba *et al.* 2008; Vale *et al.* 1987). In addition, NH_4^+ inhibits the translocation of K from roots to shoots. Inhibition of K^+ can be alleviated by increasing the external K^+ concentration (Santa-Maria *et al.* 2000). In contrast, Surendran (2005) found that K and N application had a positive effect on K (and N and P) availability, and increased availability of N after harvest when 50 kg K_2O/ha was basal applied once at planting.

The positive effect of NH_4^+ - N on K availability may be attributed to reduced fixation of K by the presence NH_4 ions that are known to compete with K for fixation sites in some clays. In related studies, in rice (Bahmaniar and Ranjbar 2007b) and barley (Endris and Mohammed 2007), increasing K application increased the uptake of both K and N. Bahmaniar and Ranjbar (2007b) used both pot and field experiments to test the effects of different levels of N and K applications on rice growth and yield parameters. They found that the interaction effects of N and K application on plant height, total dry matter, panicle grain number and grain yield were different in field in selected cultivars, but in pot experiment these differences were significant only for length and width of flag leaf.

Beecher *et al.* (1994) and Brohi *et al.* (1998) found that N increased the straw and grain yield of rice plant in the field with significant positive interactions with K. However, in pot trials no interaction between N and K was observed, potentially because the smaller soil volumes in pot trials resulted in greater competitive inhibition of K uptake by higher NH_4^+ concentrations in solution.

On calcareous soils, such as those in parts of Iraq, applying K fertiliser will decrease the adverse effects of urea on plant growth by improving K status of the plant and through decreased rhizosphere soil pH which may reduce ammonia volatilisation (Weiming and Zhiyu 1987).

2.3.9.3 **Potassium-sulphur interaction**

Sulphur plays an essential role in improving leaf area index, dry matter production, protein synthesis, and harvest index resulting in increased rice yield (Chaturvedi 2005; Sudha and Chandini 2002). Rahman *et al.* (2007) conducted a field experiment in Bangladesh into the effects of S application on K uptake. The result showed that the K uptake by grain was increased by 99% at application rates of 10 kg S/ha. For straw, K uptake increased by 87% at 40 kg S/ha. Furthermore, S positively influenced the grain yield, panicle length, 1000-grain weight, filled grain panicle of rice crops when applied at 20 kg S/ha with NPK (Uddin *et al.* 2002). Zaman *et al.* (2002) found that the combination of K and S (as magnesium sulphate) improved salt tolerance and increased dry matter and had a positive effect on K uptake. This is attributed to the synergistic relationship between S and K, which plays an important role in maintaining water content of plant tissues due to a complementary ion effect. In addition, alleviating S deficiency improved plant growth, and therefore increased K uptake.

2.3.10 Critical level of potassium in rice

Adequate tissue concentrations in rice at tillering range between 1.8 and 2.6%, and responses to applied K may occur below these values (Table 2.1) (Hill *et al*. 1998; Dorji and Uden 2003). In most rice cultivars, K deficiency appears if the range of K concentration is less than 1.5% at panicle initiation (PI). Dobermann and Fairhurst (2000) argued that the critical level of K in rice varied according to the growth stage. For example, the critical level for K deficiency was < 1.5% in the youngest leaf at tillering to PI, < 1.2% in flag leaf and straw during flowering and maturity. In addition K concentration of > 2% in mature leaves is very important for increasing the number of spikelets per panicle.

Table 2.1 Potassium critical level in youngest fully expanded leaf or flag leaf of rice plants (Hill et al. 1998).

K (% extractable) in rice plant				
	Mid. Tillering	Max. Tillering	Panicle initiation	Flag leaf
Critical	1.4	1.2	1.0	1.0
Adequate	1.4 – 2.8	1.2 – 2.4	1.2 – 2.4	1.2 – 2.2

The range of K concentrations in different plant parts throughout Asia demonstrates the high straw K content maintained by rice (Table 2.2) (Dobermann and Fairhurst 2000).

Table 2.2 Potassium content of modern rice cultivars (n=1300) (Dobermann and Fairhurst 2000).

K content (%)			
Plant part	Grain	Straw	Unfilled spikelets
Typical observed range	0.22 – 0.31	1.17 – 1.68	0. 61 – 1.20
Observed average	0.27	1.39	1.07

2.3.11 Rice response to potassium fertilisation

Numerous studies have shown that K fertilisation is crucial to increase growth and productivity of rice (Barbosa Filho and Yamada 2002; Brohi *et al.* 2000 ; Fageria *et al.* 1997). Additional fertiliser application increases rice yield rapidly to a maximum before leveling off as a quadratic function (Barker *et al.* 1985).

According to Mehdi *et al.* (2001), K concentration increased by 19 – 37% in rice grain and 7 – 14% in straw over control when 62.5 kg K/ha was applied to soils with moderate K concentrations (74 – 109 mg/kg), potentially also indicating luxury uptake.

Potassium fertiliser positively affects flag leaf width, harvest index and grain maturation in rice (Bahmaniar and Ranjbar 2007b; Bansall *et al.* 1985). Bohra and Doerffling (1993) found that K application increased the number of spikelets, yield, increased the K concentration in straw and enhanced photosynthetic activity under saline conditions. The addition of K improved the K:N ratio, plant height, tiller number, and shoot dry weight at flowering period when applied as a full basal and half basal plus half top dressing at the flowering stage on two rice cultivars. The growth of both cultivars was optimised when K was applied as a basal fertiliser. Leaf chlorophyll content increased and leaf senescence was delayed with increased K application (Dobermann and Fairhurst 2000; Nanda and Agrawal 2006).

Potassium application also indirectly increases rice yield through enhanced pest and disease resistance. Williams and Smith (2001) and Linquist *et al.* (2008) observed decreased stem rot and aggregate sheath spot of rice following K application. Potassium has also been demonstrated to restrict insect damage resulting in high yields (Dobermann and Fairhurst 2000).

Rice yield response to K fertilisers has been demonstrated by a number of studies. Surendran (2005), investigated the effects of the application of K fertiliser on the growth and the yield of rice during two cropping seasons (kharif and rabi) and found that plant height, number of tillers, number of filled grain in a panicle and the length of a panicle were increased when 42 kg K/ha was applied in two split doses of 21 kg K/ha at tillering and 21 kg K/ha at panicle initiation (PI). Due to K application at tillering, K requirements at panicle initiation were met by the naturally available soil K, resulting in increased grain and straw yields in both seasons.

Qixiang *et al.* (1998), working in two locations having alluvial and red sandy soil to assess the response of earlier and late rice yield to K application also found that the yield of rice was increased by increasing the K fertiliser levels (Table 2.3). However, the response of rice planted later in the season to K application is greater than early planted rice because earlier planted rice can access K released from the previous season's rice straw before it is leached below the root zone.

In most reported trials, application of between 40 and 190 kg K/ha is enough to increase rice yields by approximately 4 – 30% on average (Table 2.3).

Table 2.3 Effect of different levels of K on yield of rice under flooded field conditions.

Soil	K status	Levels K (kg/ha)	Increase in yield (%)	Refs.
Loam, loamy sand and sandy loam	Critical level K 0.19 – 0.28 $cmol_c$/ kg	62.5	4 – 36	Mehdi *et al.* (2001)
Alluvial	Highly negative balance.	84	11	Regmi *et al.* (2002)
1-Clay loam 2-Clay loam 3-Sandy loam 4-Sandy loam	Negative balance. 0.17 $cmol_c$/kg 0.08 - 0.18 $cmol_c$/kg 0.05 $cmol_c$/kg 0.03 - 0.09 $cmol_c$/kg	50 66	16 30	Maih *et al.* (2008)*
Clay loam	K deficient soil	104	9	Linquist *et al.* (2008)
Alluvial Red sandy	Low in available K	112	24 – 30 17 – 19	Qixiang *et al.* (1998)
Not provided	Low in available K	46 186	18 26	Dunn *et al.* (2004a)
Different soil textures at 9 sites in 5 Asian countries	0.28 $cmol_c$/kg	44	5	Dobermann and Cassman (1996)

*An experiment was established in dry land.

Much research has also shown that the recommended applications of K are dependent on the K status of the soil (Table 2.4). Variation in K response to similar K application rates may be related to differences in K fixation, and variable release of K from mineral phases in the soil (Bansal *et al*. 1985).

Table 2.4 Fertiliser K recommendations.

Range of exchangeable K (mg/kg)	K status	Recommended K	Refs.
0-25 26-50	Low	83 kg/ha 42 kg/ha	Barbosa Filho and Yamada (2002)
–	Based on K soil tests	75 - 300 kg/ha	White (2006)
0 – 25 25 – 50 > 50	Low Medium High	100 kg/ha 80 kg/ha 60 kg/ha	Asch *et al.* (1999)
47	insufficient	60 kg/ha	Fageria (2001).

Potassium requirements differ due to changing soil conditions, and is dependent on the soils ability to provide K to plants, while other factors including the type of K minerals in soil, soil moisture and temperature, soil aeration and oxygen level, CEC, rooting depth and subsoil K levels also affected the soils ability to provide K (Frank 2008).

2.3.12 Potassium and quality of rice seeds

Potassium applications can result not only in increased rice production but also impact on the quality, and chemical composition, of the grain (Tran *et al.* 2001). The presence of K is important for protein synthesis and sugar content in seeds and these are correlated with rice quality (Delma 1999). Quality of rice can be affected by K, due to the important role K plays in increasing husk ratio and husking efficiency and decreasing Brewer's rice ratio. However, there was no effect of K application on husk percentage, head rice and genetic expression of quality factors for both cultivars (Bahmaniar and Ranjbar 2007a).

2.3.13 Potassium deficiency symptoms in rice

The symptoms of K deficiency in rice include: thin stems, darker green older leaves, senescing to yellow and then brown from the margins and progressing with severity to affect younger leaves also (Dobermann and Fairhurst 2000; Dunn *et al.* 2004b; Hosier 1999). Potassium is a highly mobile nutrient in plant tissues and during periods of starvation, plants preferentially remobilise available K from older leaves and translocate it to younger leaves where it is required (Brady and Weil 2002; Dunn and Stevens 2004; Ehrler and Bernstein 1958; Nanda and Agrawal 2006).

Potassium deficiency reduces starch accumulation in the rice stem, which may lead to increased risk of lodging resulting in decreased stem strength (Brady and Weil 2002 and Kono and Takahashi 1961 in Hosier 1999).

Total root dry matter production and root morphological parameters such as length, surface area, volume and count of lateral roots were reduced under low K (Jia *et al.* 2008). Yan *et al.* (2008) also observed that root growth of selected rice cultivars was reduced under low K.

2.3.14 Factors Affecting Potassium Deficiency

Potassium is a mobile ion in sandier soil, where considerable losses due to leaching are a significant issue (Alfaro *et al.* 2004). Although leaching of nutrients such as Ca, Mg, and potentially K can be appreciable in paddy fields (Katoh *et al.* 2003). Potassium leaching losses were dependent on the amounts of available soil K; which is related to the soil type; consequently, bigger K leaching losses might be expected from sandy soils than from clayey soils (Alfaro *et al.* 2004). This has also been demonstrated by Dobermann and Fairhurst (2000) who reported that one of many factors that cause K deficiency in plants is high leaching losses. Potassium deficiency can also be caused by a large concentration of bicarbonate HCO_3^- in irrigation water, surplus Mg in soils, and reduced substances such as, Fe_2^+, H_2S and organic acids in compacted soils (Romheld and Kirkby 2010).

2.3.15 Plant Potassium Uptake

Potassium is absorbed by plant from the soil solution (Nursyamsi *et al.* 2008). Potassium ions (K^+) move from the soil solution to the plant roots by three mechanisms: (i) root interception, (ii) mass flow and (iii) diffusion (Barber 1984; Havlin *et al.* 2005). Of these mechanisms, diffusion is the most important for K translocation to the plants. However, mass flow can play a dominant role in supplying plants with K if the concentration of K in the soil solution is high (Ruiz *et al.* 1999). According to Rosolem *et al.* (2003) although less than 1% of the total K uptake by plants is contributed by root interception, an increase in root interception of soil K, mass flow and diffusion as a result to K application is expected because there is an increase of K^+ in solution.

Potassium uptake by plant tissue is an active process requiring metabolic energy to proceed as K is removed from solution against a concentration gradient (Mengel *et al.* 2001). Uptake is driven through control of plant cell membrane potential and permeability by the ATPase or ATP–powered pump. This activity is achieved through specific channels in different membranes such as the plasma membrane, vascular membrane, and the inner and outer membranes of plastids. Multiple membrane proteins are needed to adapt to changing extra-cellular environments and nutrient availability. According to electrophysiological and molecular studies, there are two active mechanisms for K^+ transportation into plant roots: (a) high-affinity K transporters (HAKTs); and (b) low-affinity K transporters (LAKTs). High-affinity K^+ uptake is particularly important when the concentration of K^+ in the soil solution is low whereas LAKTs are important in conditions of adequate soil-solution K levels (Kant and Kafkafi 2005; Martínez-Cordero *et al.* 2005). Leonard (1985) and Maathuis (1998) in Pettigrew (2008) noted that high-affinity K^+ uptake involves an energy-dependent (ATP) inward K^+ pump against an electrochemical gradient usually in combination with an outflow of either H^+ or Na^+. The low-affinity K^+ uptake can be thought of as a passive influx of K^+ down an electrochemical gradient using specific inward rectifying K channels. On the other hand, the presence of Na^+ ions in soil solution may impair or even inhibit uptake into and movement of K^+ within the root tissues (Martínez-Cordero *et al.* 2005).

Potassium uptake is also decreased by low temperature, with optimum uptake occurring in soil temperatures between 16 and 27^{o}C (Frank 2000). High Ca^{2+} and Mg^{2+} activity also lowers K uptake (Havlin *et al.* 2005). Though, K fertiliser application can also decrease uptake of divalent cations in turn (Fageria 1983; Smith 1974).

Soil-related factors notwithstanding, the stage of plant growth also plays an important role in determining K uptake. In rice the uptake of K was found to increase during the tillering period, and approximately 60 to 80% of total K uptake occurs through week four to six after planting, and this corresponds with vigorous vegetative growth, with maximum K uptake during the grain-filling period (Slaton *et al.* 2004). Nanda and Agrawal (2006) noted that the peak of K^+ uptake occurred during the reproductive stage as long as the amount of soil-solution was not limiting. However, under low soil-solution K there can be a marked reduction in K uptake, irrespective of plant growth stage.

2.3.16 Potassium removal by rice

Similar to most intensive production systems considerable K is removed in rice grain (Panaullah *et al*. 2006). Most systems, even fertilised systems, exhibit strong negative K balances (Bajaj-Singh *et al.* 2004). Rice yields between 5 and 8 t/ha can remove between 130 and 200 kg K/ha (Dobermann and Cassman 1996b; Imas and Magen 2000). In fact, Dobermann *et al.* (1998) reported that the slope of the relationship between K uptake and grain yield varied from 30 – 110 kg grain/kg K absorbed due to the tendency of K to be taken up when available, in luxury concentrations and in excess of plant demand. Luxury K uptake highlights the importance of stubble retention.

2.4 Effect of application methods on rice production

The use of chemical fertilisers in crop fields is a very important strategy to increase yields (Uphoff 2007). Based on the climatic conditions, soil type and available K test, total amount of nutrients, tilth system and crop type, various methods such as soil and foliar fertiliser application have been recommended (Mengel *et al.* 2001; Tisdale *et al.* 1993; Wolf 1999). Foliar application of K is a method of avoiding nutrient deficiency in the life cycle of a plant through bypassing reactions that may limit availability of K to roots in the soil (Jamal *et al*. 2006; McLaren and Cameron 1996). Foliar application of fertilisers acts as supplement to soil application. It plays an essential role in correcting nutrient deficiency in plants. It also avoids interaction with other nutrients (Din *et al.* 2001), counteracts the leaching losses of K (Manjappa *et al*. 2008) and provides nutrients to crops for higher yield (Arif *et al.* 2006). Dunn and Stevens (2005) indicated that the foliar application of 10.8 kg K/ha from KNO_3 increased the strength of stem and reduced lodging by 60% in Baldo rice. According to Peyvast *et al.* (2009) and Wojcik (2004) combined foliar and soil applications increased the crop yield and enhanced grain quality. Din *et al.* (2001) reported that the yields of grain and straw of rice were increased by both soil and foliar applications even under different saline conditions.

In a pot culture experiment, Manjappa *et al.* (2008) observed foliar applications of 1% at 10 g/L of muriate of potash (MOP) increased grain yield by 17% when applied 60 days after planting (DAP). Earlier application (45 DAP) was less effective as yield increases were 12% most likely due to matching application to peak uptake demand in the rice life cycle. A parallel field program failed to observe significant responses to soil application except when supplemented with foliar K.

Din *et al.* (2001) conducted a pot experiment comparing foliar and soil application of K on rice and observed an 18% increase in tiller number when both foliar and soil K were applied.

Many studies have been shown the effect of K on rice yield and its components in natural soil conditions. But there are very few studies concerning the effect of K on rice yield in soils affected by salt (Mehdi *et al.* 2007). Foliar application of macronutrients such as K assists plants from getting temporary stress caused by high moisture, salinity and competition, and is most important when nutrients are strongly fixed by soils, or when the availability of nutrient in the soil is low foliar application of K has the benefit to rapidly correct K deficiency (Mengel 2002; Wojcik 2004).

2.5 Lodging and potassium

Lodging seems to be a physiological phenomenon rather than a character of cultivar (Basak *et al.* 1962). It is an important limiting factor to the yield and quality of rice and many other cereal crops (Kashiwagi *et al.* 2008; Kashiwagi *et al.* 2010; Moldenhaure and Moldenhaure 1994; Mu *et al.* 2004; Setter *et al.* 1997; Tams 2004).

According to Hitaka and Kobayashi (1963) and Kashiwagi *et al.* (2005), lodging prevents water and nutrient transport through the xylem and phloem, leading to reduced assimilation, which affects grain filling. Lodging also makes harvest difficult and exposes grain to soil and moisture damage, reducing grain quality. Among the major factors that increase susceptibility of plants to lodging, is the use of high levels of N fertiliser (Haque *et al* 2006; Samonte *et al.* 2006). In a related study on rice lodging, Williams and Smith (2001) and Mahbub *et al.* (2006), demonstrated that high N levels increased lodging due to the effect of N in producing tall and weak stemmed plants. Earlier, Akiyama and Yingchol (1971) reported that high N fertiliser decreased the grain yield in Gow Ruang-88 rice cultivar, a tall cultivar exceeding 1.8 m, due to lodging before harvest. Stevens and Tanner (1999) and Stevens *et al.* (2001) found that 96% of Baldo rice cultivar, 107 – 122 cm tall, succumbed to lodging when N was applied at a rate of 235 kg/ha and that no lodging was observed at 34 kg/ha. Similarly, Hartley and Milthorpe (1982) found that 50% of Calrose and Kulu rice cultivars, 80 – 110 cm tall, had lodged at 75 kg N/ha and 50 – 100% of plants had lodged at both 150 and 225 kg N/ha.

There also appears to be a strong positive relationship between N fertilisation and lodging on other cereal crops such as wheat (Stapper and Fischer 1990; Tripathi *et al.* 2004). For instance, Garg *et al.* (1973) reported that application of 200 kg N/ha decreased breaking strength of the 2nd internode, leading to increased lodging. Crook and Ennos (1995) also reported stem strength was reduced by 20% as N fertiliser rate increased from 160 to 240 kg/ha. There is a direct relationship between stem diameter and stem weight with lodging resistance and stem breaking strength (Zuber *et al*. 1999).

The height of a plant may affect lodging potential with evidence shorter, stiffer straws reduce lodging incidence in cereals (Berry *et al.* 2000; Mu *et al.* 2004; Stapper and Fischer 1990). Although lodging may be observed even where semi-dwarf varieties are grown under high N conditions (Tripathi *et al.* 2005; Hartley and Milthorpe 1982). Islam *et al.* (2007) suggested that the height of rice plants can be increased up to 120 cm without lodging if they have high ability to resist breakage and maintain high dry weight per unit length. In addition, tight leaf wrapping and stiff internodes can assist in increasing resistance of the stems to lodging (Moldenhaure and Moldenhaure 1994).

Several studies have shown that the influence of lodging on yield loss occurs in two ways: first, it reduces the process of photosynthesis; and second, it creates suitable conditions for disease outbreak and increases the breakage of the stems and difficulties in harvesting (Mobasser *et al.* 2009; Setter *et al.* 1997; Weber and Fehr 1966).

During lodging, damage can manifest in three ways: breakage, bending, and rolling of stems (Fageria *et al.* 2006; Hoshikawa and Wang 1990). Of these three mechanisms, stem bending is the most damaging to susceptible lowland rice cultivars (Koshiwagi *et al.* 2008). Hoshikawa and Wang (1990) described that lodging occurred between internodes four and five and in the direction of the minor axis, and rice was more sensitive to lodging during the maturity period. Hoshikawa and Wang (1990) and Futakuchi *et al.* (2008) reported that the stem length of plants and the weight of panicles were critical factors in the lodging of rice. Conversely, rice grown through the system of rice intensification (SRI), has strong roots and tillers, high K concentration, thick stem diameter and great extent to which the sheath of leaf surrounds the stem, all of which, were important factors in reducing rice lodging (Balasubramanian *et al.* 2003; Fageria *et al.* 2006; Kumar 2009; Uphoff 2007).

Lodging can also result from failure in root systems, which are weakly developed and lodging often occurs when plant growth is slow in soils that are low in available K. Root lodging is influenced by structural plant traits such as inadequate standing power. Root lodging is also cultivar dependent as well as affected by the environmental growing conditions. Lodging may take place as a result of irreversible bending or breaking of the roots. However, a more developed root system provides resistance to lodging which may occur by loss of anchorage. Rice plants are more likely to suffer root lodging, leaning from the crown due to disturbance of root system, than stem lodging, the displacement of stems from their upright position (Kant and Kafkafi 2002; Oladokun and Ennos 2006; Pinthus 1974). The resistance of some cultivars to root lodging is possible, while still remaining susceptible to stem lodging, and selection of cultivars according to the likely environment and targeted crop management is critical to minimising both types of lodging and improve any specific weakness (Berry *et al.* 2003).

Potassium enables resistance to lodging (Kant and Kafkafi 2002) through increased straw and stem hardness and increased cell wall thickness (Romheld and Kirkby 2010).

Potassium applications also increase starch accumulation in cell walls, which leads to greater stem strength and reduced lodging (Stevens *et al.* 2001). Similarly, Dunn and Stevens (2005) found that lodging of rice cultivar (Baldo) was considerably reduced by foliar applications of potassium nitrate (KNO_3) at midseason due to increased stem strength, which is associated with suitable K nutrition.

2.6 Effects of salinity on rice

Salinity has received much attention worldwide due to negative effects on rice crop production. Rice is considered to be a salt sensitive crop (Abdullah *et al.*2001; Mass and Hoffman 1977), affected at every growth stage (Heenan *et al.* 1988; Hoa *et al.*1998; Islam *et al.* 2007 ; Walia *et al.*2007; Zeng and Shannon 2000). Rice yield has reportedly been reduced by 50% under saline conditions near an EC (saturated extract) of 4.3 dS/m (Heenan *et al.* 1988), 6 dS/m (Zeng *et al.* 2002) and 8 dS/m (Asch and Wopereis 2001) compared with non-saline conditions. Saleque *et al.* (2005) reported that under salinity level of 8.75 dS/m, the grain yield of rice reduced by 45% due to high spikelet sterility.

The sterility of rice increased by 29% resulting in yield loss under saline conditions (Shereen *et al.* 2005). Furthermore, increasing salinity levels decrease the grain yield and the number of tillers of spikelet in the panicles as well as the number of tillers per plant (Din *et al.* 2001). In contrast there was no effect of salinity on kernel weight in rice, and this finding mirrors findings with barley and salinity (Endris and Mohammed 2007; Islam *et al.* 2007; Zeng and Shannon 2000; Zeng *et al.* 2002).

Small applications of soil or foliarly applied K_2SO_4 increased rice growth under saline conditions (Din *et al*. 2001). Grain: straw ratio increases with K application and decreases with increasing salinity levels, due to the effects of osmotic pressure, nutritional imbalance and the effects of specific ion (Flowers *et al.* 1991) potentially through regulation of stomatal opening and closing (Din *et al*. 2001).

Under varying saline conditions, Ca^{2+} and K^+ content of straw was decreased, while Na^+ concentration was increased as salinity increased to 15 dS/m (Bohra and Doerffling 1993; Islam *et al*. 2007). High concentration of Na^+ induces K deficiency, greatly decreases leaf chlorophyll concentration, ultimately reducing growth and water use of the plant and decreasing the permeability of membranes (Heenan *et al.* 1988; Islam *et al*. 2007; Kaya *et al.* 2001). Heenan *et al.* (1988) mentioned that K^+, Na^+ or Na:K concentrations in the shoots are useful indicators for assessing the impact of salinity, just as selectivity of K^+-Na^+ ions are an important indicator of salinity tolerance in crops (Zaman *et al.* 2002).

2.7 Carbohydrate production and yield

Carbohydrates include sugars, starch and other polysaccharides. Their concentration in both the leaf sheaths and stems of rice plants typically peaks before panicle appearance (Chen *et al.* 1980). The stored carbohydrates are either retransferred to the panicles, or used in respiration during the grain-filling period (Nagata *et al.* 2001; Yoshida 1972).

Nitrogen increases vegetative growth and reduces carbohydrate accumulation in rice prior to late initiation stage of spikelets, and therefore enhances the accumulation of carbohydrate after the late stage of spikelet initiation. Chen *et al.* (1980) found that the total nonstructural carbohydrate concentration (TNC) decreased during the 40 DAT, but it increased considerably 50 DAT, while noting that the TNC accumulated in both leaf sheath and stem after transplanting and peaked during the spikelet infilling period. According to Wada *et al.* (1986) the percentage of carbohydrate in rice grain is higher during the ripening period than the quantity stored in shoots at the heading stage. The amount of carbohydrate present after spikelet initiation determines the number of spikelets that survive up to maturity and the weight of the rice grains, which are important parameters in determination of rice grain yield.

According to Abdullah *et al.* (2001), any process that reduces the quantity of carbohydrates available after spikelet initiation or affects its translocation from the leaves to floral parts results in failure of grain filling. They found that addition of N fertilisers was instrumental in increasing the percentage of mature rice grains. In addition, they also found that under saline soil conditions, high Na^+ accumulation and low K^+ content in floral organs, significantly reduced starch synthesis, resulting in increased seed sterility, which is one of the main causes of the yield loss (Shereen *et al.* 2005).

2.8 Summary

From this chapter, the literature indicates that K application offers enormous benefits in terms of rice growth and grain yields. Most importantly, rice cultivars vary in their responses to applied K, depending on the local environmental conditions where the crop is grown. Increased tolerance to salinity and resistance to lodging are the two principal mechanisms through which K improves the productivity of rice under saline environments. Of equal importance in enhancing rice growth and grain yields is the balance between K and N nutrition. Unfortunately, most of the studies on rice responses to K and N under saline environments have been conducted in isolation. In Iraq, farmers have incorporated the practice of fertilising rice with N and P for over 60 years as part of government effort to increase rice production to meet the huge domestic demands. Potassium has not been prioritized as a much needed nutrient under the saline conditions in Iraq. Consequently, lodging alone accounts for 25 – 30% of rice production losses, especially for the most popular cultivar (Amber33). No studies have been conducted to determine how this cultivar might respond to K fertiliser. This particular study was designed to determine the K fertilisation strategy for reduced lodging and mitigation of the adverse effects of salinity. Furthermore, field evidence of lodging in Iraqi conditions suggests lodging as a consequence of basal root failure, rather than stem or panicle breakage. Hence the effect of K application on root system development and structure is important in outlining the mechanism by which K application may reduce lodging incidence. Although evidence in the literature supports a role for foliar K application in overcoming K deficit in saline conditions, the limited ability of Iraqi farmers to apply K later in the growing season using foliar application techniques resulted in a decision to not investigate that further. Consequently a number of experiments were conducted under Australian conditions using soil to match typical Iraqi rice production soils. These included: 1) effect of K on reducing lodging under high-N conditions 2) role of K on rice growth and yields under salinity conditions and 3) effects of K on rice root system. Experiment one was repeated at three sites under Iraqi conditions. It is hoped that the study will provide beneficial information for Iraqi farmers on the use of K for rice production, and provide directions for further research.

CHAPTER 3: POTASSIUM AND RICE UNDER HIGH N CONDITIONS IN GLASSHOUSE

3.1 Introduction

Rice (*Oryza sativa.* L) is one of the major cereal crops in Iraq. The production of rice is critical for food security. The productivity of the most common Iraqi rice cultivar, Amber33 averages 2.9 t/ha (Ministry of Planning 2007) and is relatively low compared to the production of 4.2 – 6.6 t/ha in SE Asian countries (Mutert and Fairhurst 2002). According to Iraqi farmers, lodging in Amber33 can cause up to 25 – 30% yield loss (Dr. Sabah Abid of MoA in Iraq , personal communication, March 4, 2011). Agronomic factors affecting lodging include nitrogen (N) supply (and timing) and potassium (K) and silicon (Si) nutrition. Increased and timely N supply, promoting vigorous vegetative growth and increased panicle size and weight, may result in lodging. Similarly, insufficient tissue K is known to increase lodging incidence (Kant and Kafkafi 2002). Consequently, N and K nutrition may be key factors driving lodging in Iraqi rice production systems. Improvements in crop and fertiliser management could rapidly increase rice yield. The objective of this study was to evaluate the effects of K application on lodging and growth of a range of tall, standard and semi-dwarf rice cultivars under high N input conditions.

Lodging limits both quantity and quality of rice grain and it appears to be related to cultivar differences in lodging tolerance (Basak *et al.* 1962). Thus, the level of lodging is dependent on the cultivar used and management practices. Lodging damage can happen in three ways; 1) snapping at the head, 2) breaking mid-stem due to poor stem strength and 3) basal lodging associated with poor root anchorage (Fageria *et al.* 2006; Hoshikawa and

Wang 1990), resulting in reduced yields and increased harvesting costs (Akiyama and Yingchol 1971). In rice, stem length and the strength of plants are critical factors affecting lodging incidence (Futakuchi *et al.* 2008; Hoshikawa and Wang 1990).

Nitrogen is a vital nutrient for improving the yield of any crop, including rice. Nitrogen is a significant component of amino acids and protein; it also plays an important role in enhancing both the rate of photosynthesis and the efficiency of radiation capture and conversion. Nitrogen fertiliser application increases N uptake, dry matter, tiller number and grain yield and the quality of rice (Beecher *et al.* 1994; Mae 1997). However, excess N application may increase the number of sterile spikelets resulting in decreased grain yield. High levels of N fertiliser also increase the susceptibility to lodging in cereal crops (Crook and Ennos 1995; Garg *et al.* 1973; Haque *et al.* 2006; Samonte *et al.* 2006; Stevens and Tanner 1999). High N rates increase vegetative growth and delay maturity, resulting in tall and ultimately weak plants (Williams and Smith 2001), reducing subsequent grain yield (Akiyama and Yingchole 1971; Stapper and Fischer, 1990).

Potassium is one of the essential nutrients required by plants for adequate growth and production. Improved K nutrition has been linked to reduced lodging (Balasubramanian *et al.* 2003; Fageria *et al.* 2006; Kumar 2009; Uphoff 2007). According to Kant and Kafkafi (2002) and Wolf (1999) straw and stem hardness is reduced under K deficiency. Potassium plays an important role in building cellulose to produce thick and strong cell walls (Romheld and Kirkby 2010; Kumar 2009), which increases resistance of plants to lodging.

Nitrogen and phosphorus (P) fertilisers have been widely used (276 kg/ha and 88 kg/ha per year respectively) by Iraqi farmers for a long time, while K has not been used (Al-Zubaidi *et al*. 2007). It has also been reported that Iraqi soils have a high capacity to fix K caused by the presence of dioctahedral clay minerals resulting in a very slow K release profile (Al-Zubaidi *et al.* 2004).

It is proposed that increasing Amber33 rice yield may be related to improved K nutrition and a better balance of K application with N and other essential soil nutrients. In order to better understand the effects of K additions and rice cultivars on lodging under high N conditions, an experiment was carried out with three cultivars and repeated with six cultivars using a high N rate with and without K, under glasshouse conditions at the University of New England, Australia.

3.2 Materials and methods

3.2.1 Experimental design

Two glasshouse pot experiments were undertaken during 2009-2010. In Experiment 1 three rice cultivars were grown under high N conditions during winter with or without K addition (200 mg K/kg soil), replicated four times and laid out as a complete randomised design. Experiment 2 had the same design, except that six rice cultivars were grown during summer.

A non-sodic non-saline Black Vertosol (Isbell 1996) from Oakwood in northern NSW, Australia was used and the selected chemical properties of the soil are presented in Table 3.1. The soil is regularly cropped as part of a cereal/legume rotation and has relatively low

K status (~0.2 $cmol_c/kg$) and has exhibited K deficiency symptoms in cereals in the last 3 years. The soil used in the study was collected from a depth of 10 – 20 cm.

Table 3.1 Selected soil chemical properties of a Black Vertosol from Oakwood, NSW.

Soil depth (cm)	pH[a]	EC[b] dS/m	Exchangeable bases[c] ($cmol_c/kg$)				C (%)[d]	N (%)[d]	Reserve K[e] ($cmol_c/kg$)	S (mg/kg)[f]
			Ca	Mg	K	Na				
0 – 10	6.9	0.79	31.3	20.1	0.6	0.08	1.8	0.15	0.74	6.4
10 – 20	6.8	0.64	30.3	19	0.22	0.18	1.5	0.13	0.3	9.6

[a] 1:5 soil/water suspension; [b] 1:5 soil/water extract; [c] extracted by 1:10 soil/ammonium acetate (pH7.0) solution, measured by ICP-AES; [d] Carlo Erba NA 1500; [e]Tetraphenyl-boron extractable K; [f] MCP test.

Rice seeds were supplied by the Yanco Agricultural Institute, Australia, except for Amber33, which was supplied by the Rice Research Station, Iraq. The three rice cultivars used in the initial winter experiment (Experiment 1) were Amber13, IR52713 and IR45427, while the six rice cultivars used in the second summer experiment (Experiment 2) were Amber13, IR52713, IR45427, Koshihikari, Amber33 and Basmati370. Only three cultivars were grown in the winter season due to seed availability, whereas in summer six cultivars were available. This range of cultivars was chosen to represent a continuum with respect to plant height from semi-dwarf (IR45427 and IR52713) to standard (Amber13) and tall (Amber33, Koshihikari and Basmati370) cultivars which theoretically have reduced susceptibility to lodging due to an inability to produce excessive plant canopy heights.

Seeds were germinated on June 30, 2009 for the winter experiment and November 11, 2009 for the summer experiment at 29˚C on moist filters paper in a plant growth cabinet and were irrigated with distilled water only. Similar sized seedlings were transplanted to treated soil in lined 150 mm diameter plastic pots, 150 mm deep, after one week, in a glasshouse at the University of New England, Australia.

All treatments were supplied with a high 300 mg N/kg rate from urea (CO $(NH_2)_2$ (46% N), with or without 200 mg K/kg as K_2SO_4 (45% K). Nitrogen was applied in two split applications; 150 mg N/kg applied at transplanting and 150 mg N/kg at 40 – 45 days after transplanting (DAT) at the maximum tillering stage. Potassium was added to the soils as a basal treatment prior to transplanting. In addition, P fertiliser was applied to all pots once at planting at a rate of 50 mg P/kg soil as calcium tetra hydrogen di-orthophosphate ($Ca(H_2PO_4)_2$) (24%P). Phosphorus is necessary for root development, especially during the early growth period, to ensure that rice growth is not inhibited (Brohi 1998). Sulphur (S) was applied at 82 mg S/kg in gypsum ($CaSO_4{\cdot}2H_2O$, 15% S) as a basal dose to the treatments without K in order to balance S nutrition. The small change in Ca status arising as a result of this addition is unlikely to affect K uptake as it constitutes only a small shift in Ca saturation on the soil exchange. Plants were grown to either panicle initiation or just prior to grain filling before being harvested. Shoot and root dry matter production was assessed together with cation tissue concentrations.

3.2.2 Tissue K content

Roots were collected and rinsed gently with tap water to remove the clay soil. Prior to analysis the roots were then gently rinsed with deionised water. Shoots were harvested 1 cm above ground level, separated into leaves and stem and then oven dried for 72 h at 80˚C. Roots and shoots were digested using the sealed chamber digestion method of Anderson and Henderson (1986). In brief, approximately 0.2 g of ground plant material from each sample was predigested with a mixture of 70% $HClO_4$ and 30% H_2O_2 (v/v) overnight, then placed in an oven at 80˚C for 30 minutes. Samples were repeatedly digested with peroxide until solutions were clear; they were then filtered, made up to volume and cations were measured using inductively coupled plasma atomic emission spectroscopy (ICP-AES).

3.2.3 Stem diameter and stem strength

Stem diameter and stem strength measurements were made at 72 and 91 DAT. The diameter of the stem (mm) was measured using an electronic digital vernier caliper of centrally located tillers between the first and second above ground internode (Mu *et al.* 2004). In experiment 1, the stem strength of the rice straw was assessed using a Briquette breaking machine, which commonly is used to assess the modulus of rupture as described by Moldenhauer and Moldenhauer (1994), whereas a Material Testing Machine (JJ Lloyd) was used in experiment 2 as reinstallation of the JJ Lloyd was completed in the intervening period. The stem cross-section, cut at 20 cm above the ground, was divided into two parts (bottom and top, each 10 cm long); the test was performed with increasingly heavier weights until the sample failed.

3.2.4 Plant height

Plant height (cm) measurements were made 70, 77, 84 and 91DAT from the base of the stem to the tip of the highest leaf. Records were made for the main tillers of each treatment.

3.2.5 Potassium availability and uptake

Total K uptake from the soil (K_{TU}) was calculated as a function of tissue K concentration in leaves and roots of rice (K_{TC}) as a fraction of the amount of K fertiliser applied (K_F) and the initial concentration of available K in the soil solution (K_A) expressed as a percentage using the formula below;

$$K_{TU} = K_{TC}/\ K_F + K_A \times 100$$

Total K/kg soil = Soil K availability plus applied K as fertiliser (200 mg/kg soil). From the data in (Table 3.1) the soil showed a low content (0.22 $cmol_c$/kg soil) of available K.

3.2.6 Statistical analysis

Results were analysed by analysis of variance (ANOVA) using the R statistical package (R Development Core Team 2009) and P (0.05) values were considered as significantly different results. Results were graphed using SigmaPlot, v.7.

3.3 Results

3.3.1 Visual K deficiency symptoms

This study showed that a high rate of N (300 mg N/ha) with inadequate or no K fertiliser resulted in symptoms that are associated with K deficiency in rice. Such symptoms of K deficiency in rice cultivars (Figure 3.1) were initially noticed in the older leaves followed later in the younger leaves. The yellowish brown leaf margins or dark brown necrotic spots first appeared on the tips of older leaves. Later, they were seen on the leaf edge and the leaf base. In both experiments (winter and summer), all cultivars showed visual K-deficiency symptoms, but Amber33 was the most affected cultivar by K-deficiency out of the six cultivars that were grown.

Figure 3.1 Potassium-deficiency symptoms on leaves of Amber33 cultivar grown for 71 DAT in a glasshouse on a K responsive Black Vertosol.

The morphology of rice roots was examined 91 DAT in both experiments. Root quantity increased with the addition of K regardless of the cultivar (Figures 3.2 and 3.3) (root dry weight results are provided later in Chapter 5).

Figure 3.2 Effect of potassium application (no potassium vs 200 mg K/kg) on root production of two rice (*Oryza sativa*) cultivars grown for 91 DAT in a glasshouse on a K responsive Black Vertosol in 2009.

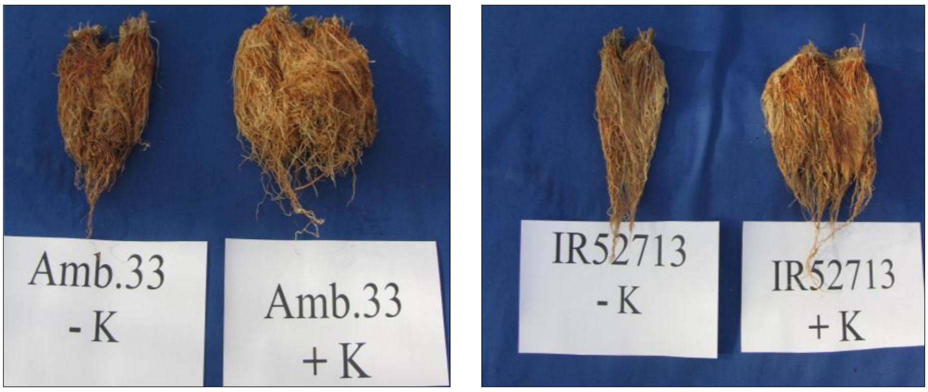


Figure 3.3 Effect of potassium application (no potassium vs 200 mg K/kg) on root production of two rice (*Oryza sativa*) cultivars grown for 91 DAT in a glasshouse on a K responsive Black Vertosol in 2010.

3.3.2 Experiment 1 (winter)

3.3.2.1 **Lodging**

Lodging was observed in all three cultivars to different extents. Lodging occurred primarily from the base of the plants (Figure 3.4).

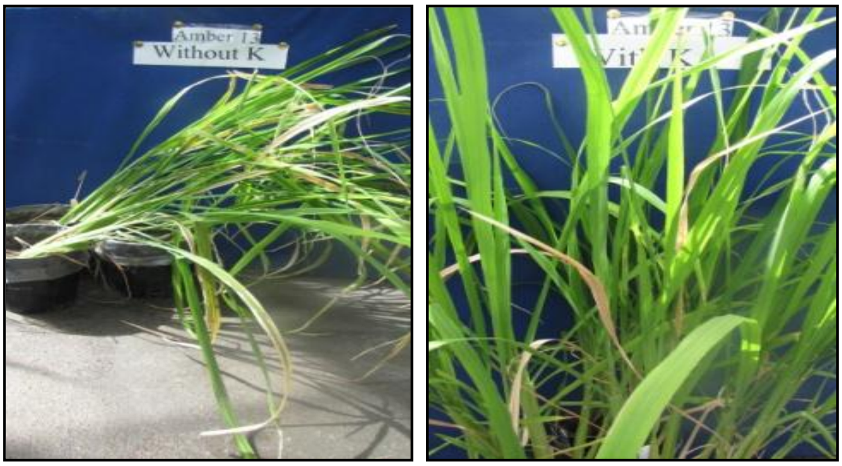


Figure 3.4 Effect of K application (no potassium vs 200 mg K/kg) on lodging of Amber13 grown for 84 days in a glasshouse on a K responsive Black Vertosol.

3.3.2.2 **Effect of K on tiller number**

There was significant ($P < 0.01$) interaction between cultivar and K treatments on tiller production (Figure 3.5). Tiller number was significantly increased by K in all cultivars, with the greatest effect being observed for IR52713.

3.3.2.3 **Effect of K on plant height**

As expected, the standard height cultivar Amber13 was taller ($P < 0.001$) than semi-dwarf rice cultivars (Figure 3.6). Potassium application increased plant height of the semi-dwarf cultivars by (13 – 30%), but there was no significant interaction ($P > 0.05$) between K and cultivar.

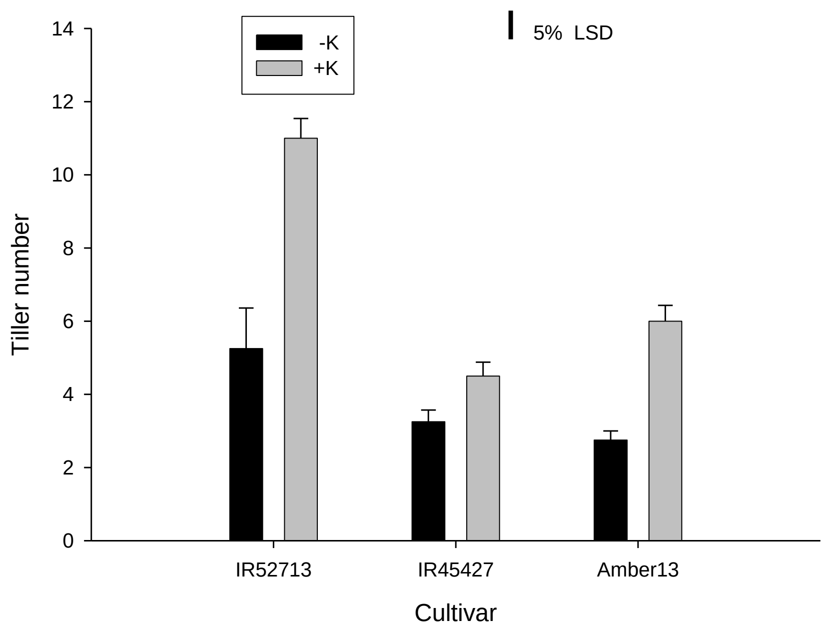


Figure 3.5 Effect of K application (no potassium vs 200 mg K/kg) on tillering of three rice (*Oryza sativa*) cultivars grown for 70 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with ± standard errors indicated by bars.

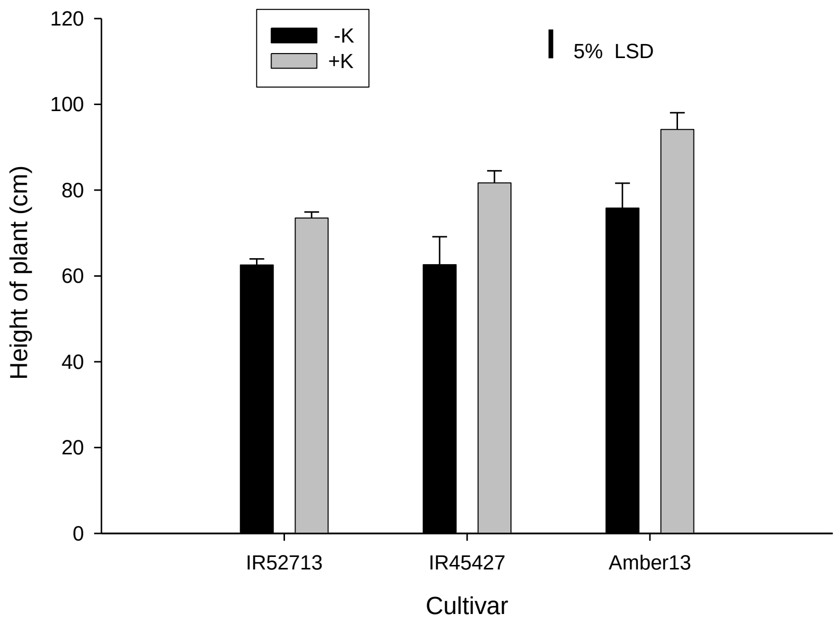


Figure 3.6 Effect of K application (no potassium vs 200 mg K/kg) on plant height (cm) of three rice (*Oryza sativa*) cultivars grown for 70 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with ± standard errors indicated by bars.

Plotted over time, the slope of plant height changes did not differ significantly ($P \geq 0.081$) between weeks 10 – 13 (Appendix 3.1).

3.3.2.4 **Effect of K on shoot dry weight**

Effect of K on shoot dry weight (SDW) of selected cultivars is presented in Figure 3.7. Shoot dry growth increased ($P < 0.001$) by 133% in Amber13, 112% in IR45427 and 108% in IR52713 following K application and there was no interaction between K and cultivar.

3.3.2.5 **Effect of K on root dry weight**

Figure 3.8 shows the effect of K on root dry weight (RDW). Potassium application increased RDW production of all cultivars although IR45427 did not respond to the same extent as the two other cultivars (there was a significant ($P < 0.01$) K by cultivar interaction). Root growth increased by a factor of 4 in IR52713 and Amber13 but by only twice as much in IR45427 following K treatment.

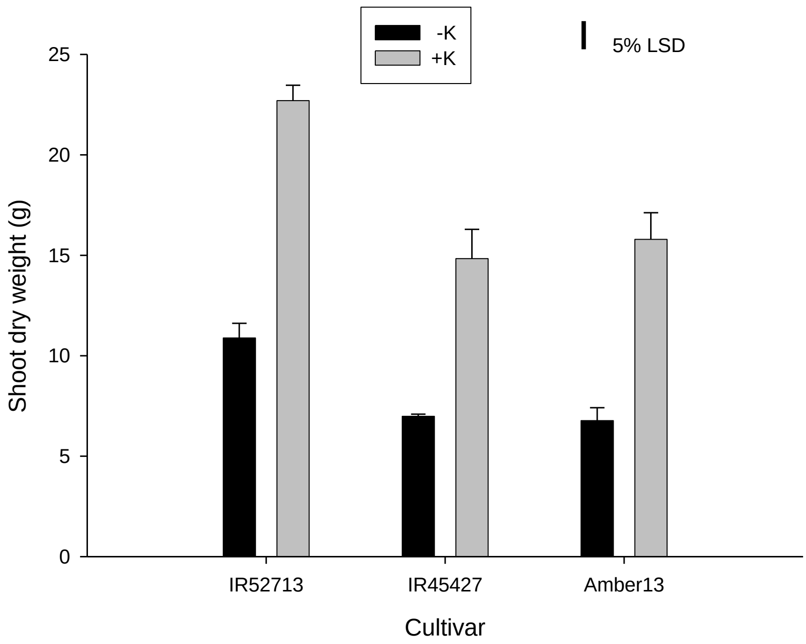


Figure 3.7 Effect of K application (no potassium vs 200 mg K/kg) on shoot dry weight (g/pot) of three rice (*Oryza sativa*) cultivars grown for 84 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with ± standard error indicated by bars.

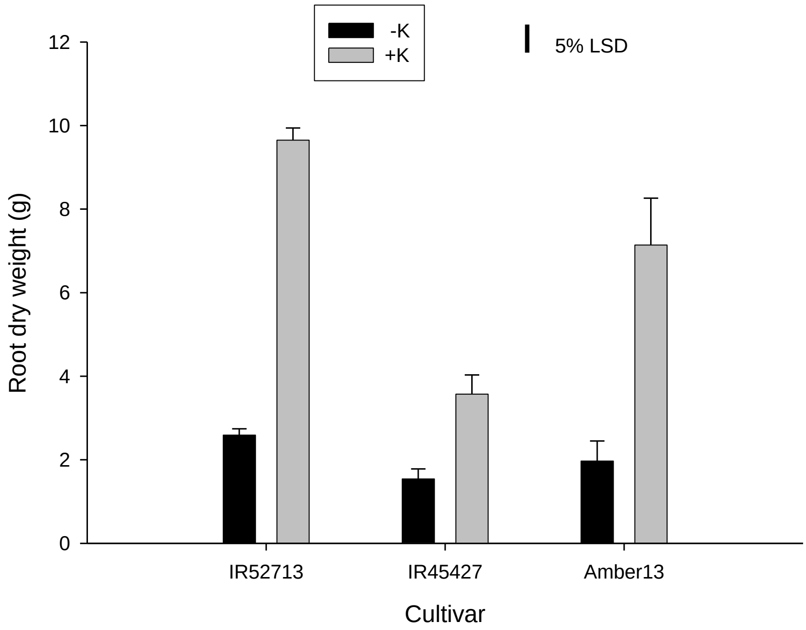


Figure 3.8 Effect of K application (no potassium vs 200 mg K/kg) on root dry weight (g/pot) of three rice (*Oryza sativa*) cultivars grown for 84 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with ± standard errors indicated by bars.

3.3.2.6 **Effect of K on plant stem diameter**

Application of K increased ($P < 0.001$) both thick and thin shoot diameters in all rice cultivars (Appendix 3.2, Figures 3.9 and 3.10) with no cultivar/K interactions. Average increases ranged from 14-32% in thick stem diameter and 56-84% in thin stem diameter. Added K fertiliser showed differences in the rate of stem thickness increase over time; for example between 11 and 12 weeks after sowing added K showed a greater stem thickness increase with Amber13 and IR45427 than either earlier or later in the measurement period (Appendix 3.3).

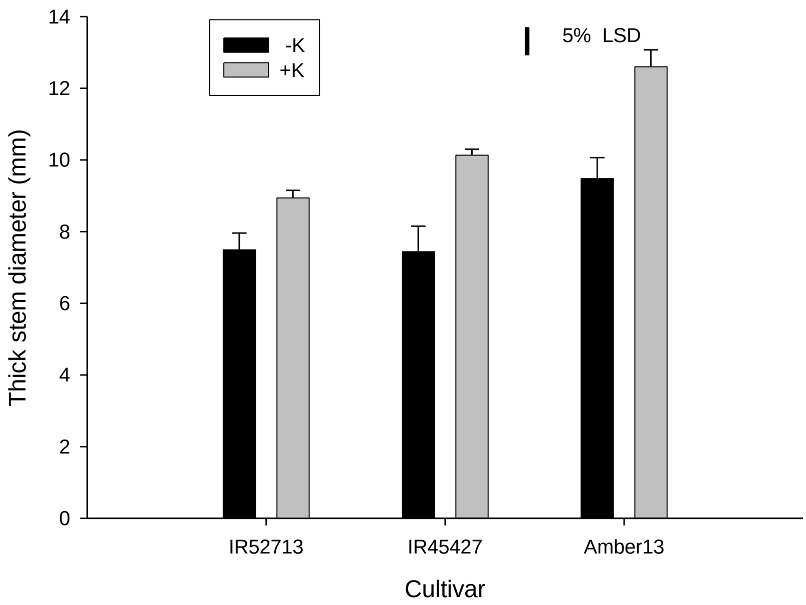


Figure 3.9 Effect of K application (no potassium vs 200 mg K/kg) on thick stem diameters (mm) of three rice (*Oryza sativa*) cultivars grown for 70 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with ± standard errors indicated by bars.

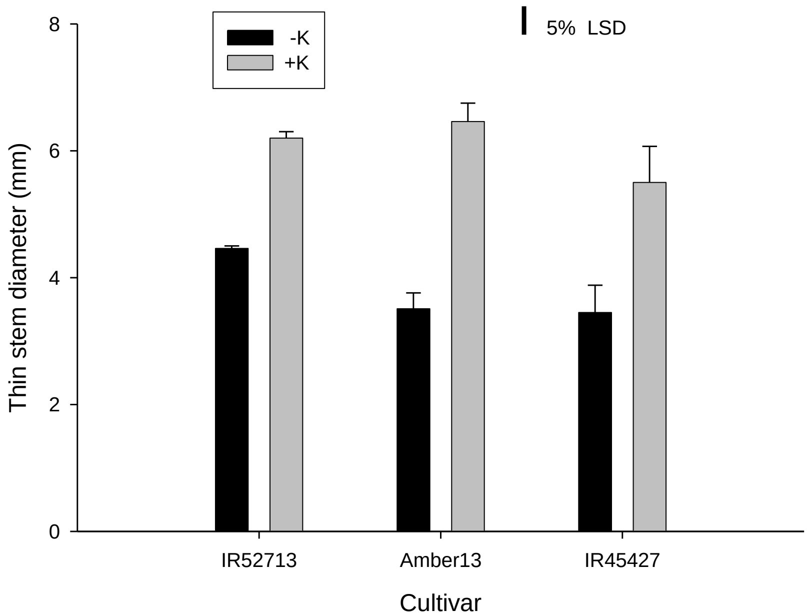


Figure 3.10 Effect of K application (no potassium vs 200 mg K/kg) on thin stem diameters (mm) of three rice (*Oryza sativa*) cultivars grown for 70 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with ± standard errors indicated by bars.

3.3.2.7 **Effects of K on plant stem strength**

Application of K significantly ($P < 0.001$) increased the lower stem strength of all three rice cultivars (Figure 3.11) with no K by cultivar interaction. Stem strength was generally higher in shorter stature rice cultivars.

There was a significant ($P < 0.05$) K by cultivar interaction in upper stem strength (Figure 3.12). Upper stem strength was higher in IR52713; upper stem strength was least affected by added K in Amber13.

3.3.2.8 **Potassium concentrations in leaf, stem and root**

Leaf, stem and root concentrations of K in the rice cultivars are shown in Table 3.2. There were interaction effects between K and cultivar following K application; IR45427 generally showed the greatest increase to K concentration in leaves and stem and Amber13 showed the greatest increase in root K level.

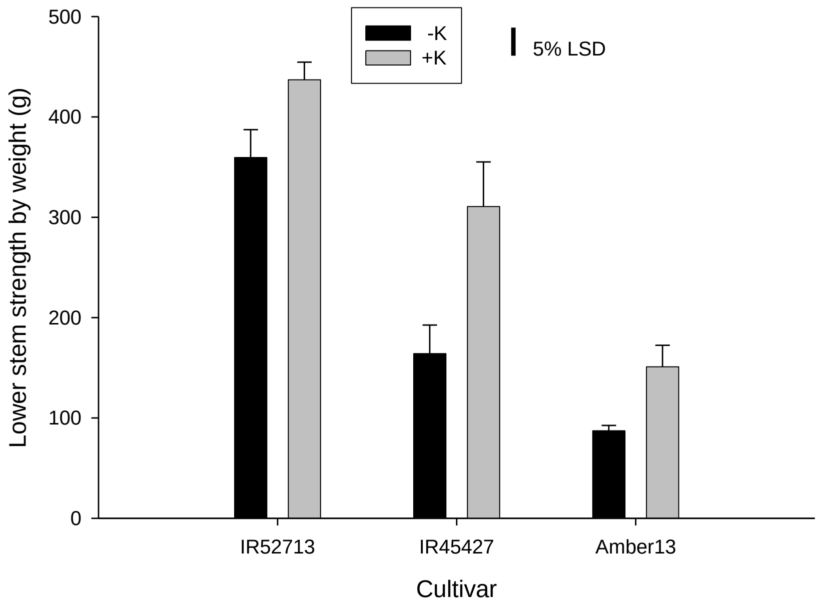


Figure 3.11 Effect of K application (no potassium vs 200 mg K/kg) on lower stem strength of three rice (*Oryza sativa*) cultivars grown for 84 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with ± standard error indicated by bars.

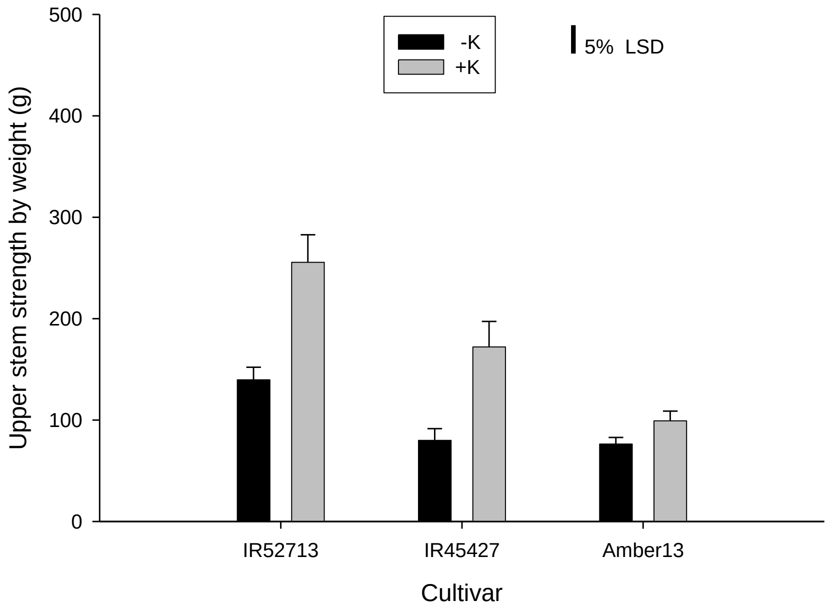


Figure 3.12 Effect of K application (no potassium vs 200 mg K/kg) on upper stem strength of three rice (*Oryza sativa*) cultivars grown for 84 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with ± standard error indicated by bars.

Table 3.2 Effect of K application (no potassium vs 200 mg K/kg) on K concentration (%) in leaves, stem and root of three rice (*Oryza sativa*) cultivars grown for 84 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with ± standard errors of the means.

Cultivar	K status	Leaf K (%)	Stem K (%)	Root K (%)	K uptake (Leaf+Root) (mg/pot)
IR52713	-K	0.46±0.05	0.57±0.10	0.30±0.06	57±4.7
IR52713	+K	1.11±0.19	1.00±0.07	0.36±0.01	284±36
IR45427	-K	0.82±0.28	0.67±0.07	0.24±0.03	41±2.6
IR45427	+K	1.75±0.16	1.61±0.38	0.45±0.01	278±42
Amber13	-K	0.55±0.12	1.09±0.03	0.28±0.01	40±4.9
Amber13	+K	1.13±0.20	1.66±0.09	0.52±0.04	208±20
LSD (0.05)		**0.39**	**0.37**	**0.07**	**52.06**

3.3.2.9 **Availability and uptake of K**

The quantity of available K in the soil was 0.22 $cmol_c$/kg (86 mg/kg, Table 3. 1). Based on preliminary data, this would require addition of K to the soil at 200 mg K/kg to increase the availability of K to a level no longer responsive to applied K. The plant K/total available K ratio significantly ($P < 0.001$) increased due to increase ($P < 0.001$) K uptake by plants (Table 3.2). The cultivars IR45427, Amber13 and IR52713 showed increases of 64, 55 and 32 %, respectively over control (zero K treatment) (Figure 3.13). IR45427 accumulated 58% more K than IR52713 in +K treatments, although both are semi-dwarf cultivars.

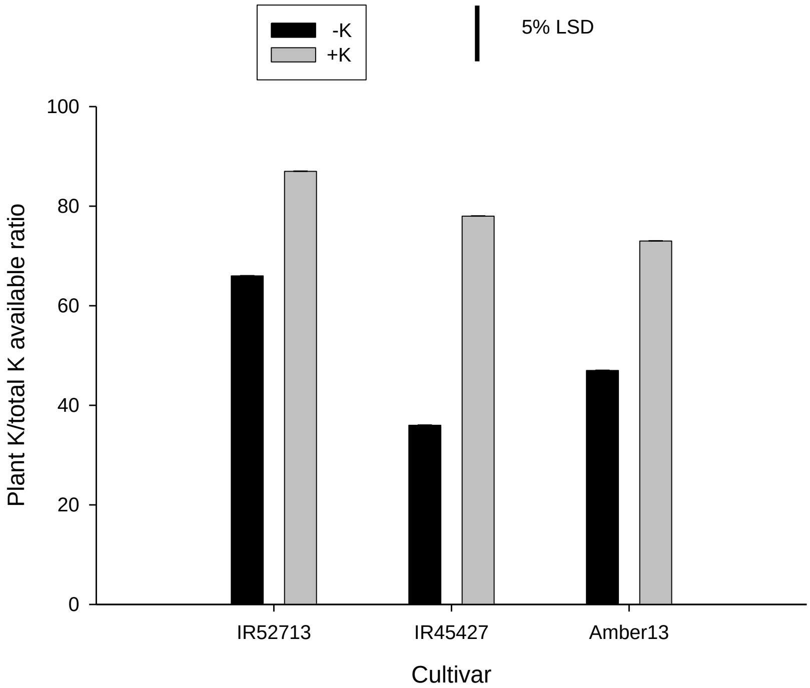


Figure 3.13 Potassium uptake ratio (plant K/applied K) of three rice (*Oryza sativa*) cultivars in winter experiment grown for 84 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with ± standard errors indicated by bars.

3.4 Experiment 2 (summer)

The structure and operation of this experiment was similar to Experiment 1, except for the increased number of rice cultivars.

3.4.1 Results

3.4.1.1 **Effect of K on tiller number**

Potassium again increased tiller production in all cultivars as in experiment 1 (Figure 3.14). Potassium increased tiller numbers ($P < 0.001$) by 33, 22, 68, 47, 41 and 59% in IR52713, IR45427, Amber13, Amber33, Koshihikari and Basmati370, respectively. However, there was no significant interaction ($P > 0.05$) between K and cultivar.

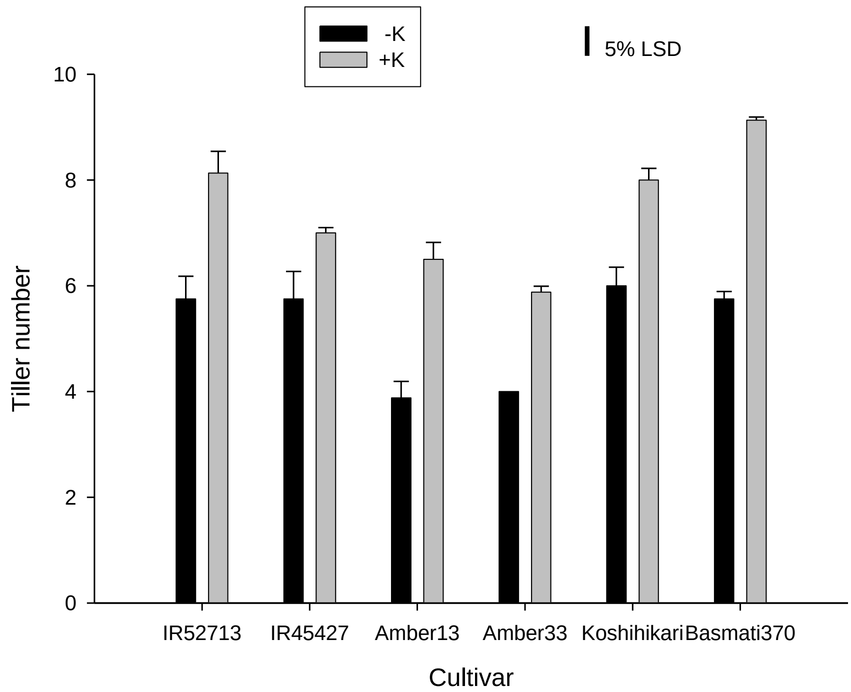


Figure 3.14 Effect of K application (no potassium vs 200 mg K/kg) on tiller production of six rice (*Oryza sativa*) cultivars grown for 70 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with ± standard errors indicated by bars.

3.4.1.2 **Effect of K on plant height**

Potassium fertiliser increased plant height ($p < 0.01$) in all six cultivars (Figure 3.15); a K by cultivar interaction occurred where IR45427 only increased in height by 11% compared with the 24% increase in height of Koshihikari. As would be expected, there was a significant (P slope=0.001) effect of time (10 – 13 WAS) on plant height (Appendix 3.4).

The result of these experiments demonstrated the importance of K nutrition at early stages of rice growth.

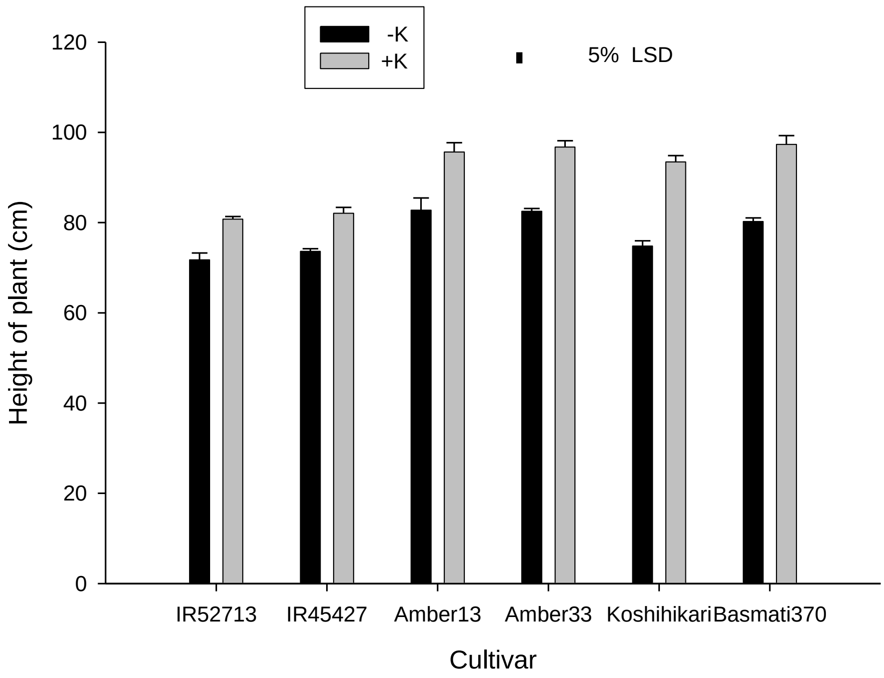


Figure 3.15 Effect of K application (no potassium vs 200 mg K/kg) on plant height (cm) of six rice (*Oryza sativa*) cultivars grown for 70 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with ± standard errors indicated by bars.

3.4.1.3 **Effect of K on shoot dry weight**

Shoot dry weight (SDW) showed a significant ($P < 0.05$) interaction between applied K fertiliser/cultivar effects (Figure 3.16). The SDW of Amber13, Amber33, Koshihikari, and Basmati370 with 200 kg K/ha showed increases of 108, 103, 104 and 132%, respectively compared with the zero K, but short cultivars (IR52713 and IR45427) recorded smaller SDW increases (86 and 70%) compared to the tall and standard height cultivars.

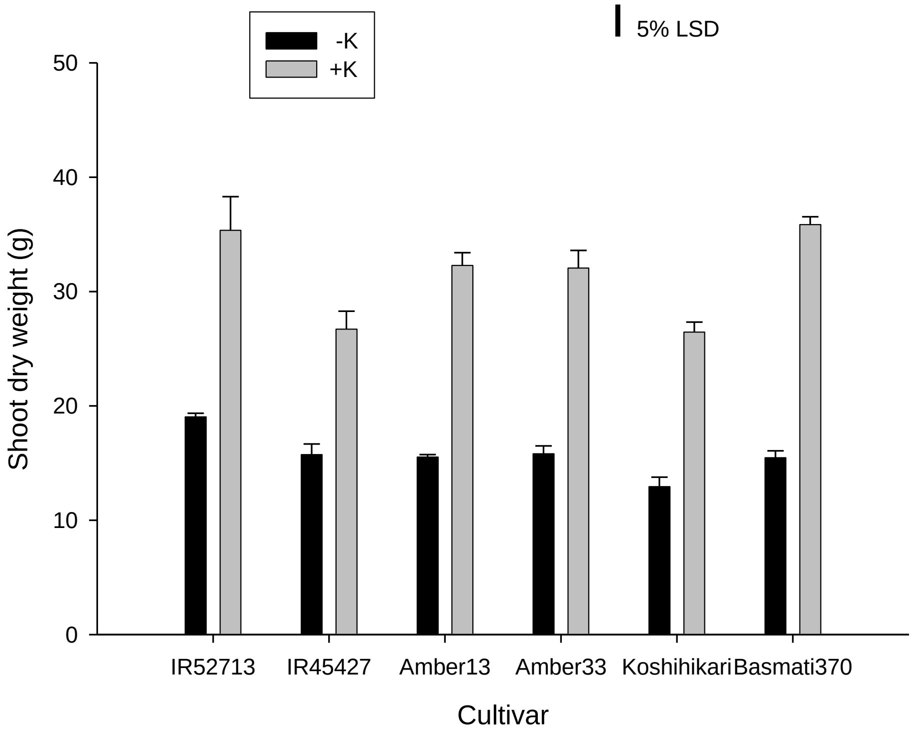


Figure 3.16 Effect of K application (no potassium vs 200 mg K/kg) on shoot dry weight (g/pot) of six rice (*Oryza sativa*) cultivars grown for 84 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with standard errors indicated by bars.

3.4.1.4 Effect of K on root dry weight

Root dry weight (RDW) increased to a greater level ($P < 0.001$) with K application than the response in shoot dry weight (Figure 3.17) with greater root growth observed following K application to taller rather than shorter statured varieties. With added K, Basmati370 showed the highest root dry weight followed by Amber13 and Amber33. The lowest dry weight was recorded in Koshihikari. In the absence of K, root dry weight varied by as little as 18% across all cultivars. However, following K application Basmati370 and the Amber cultivars increased root weight by more than 5 times, whilst Koshihikari only doubled its root dry weight.

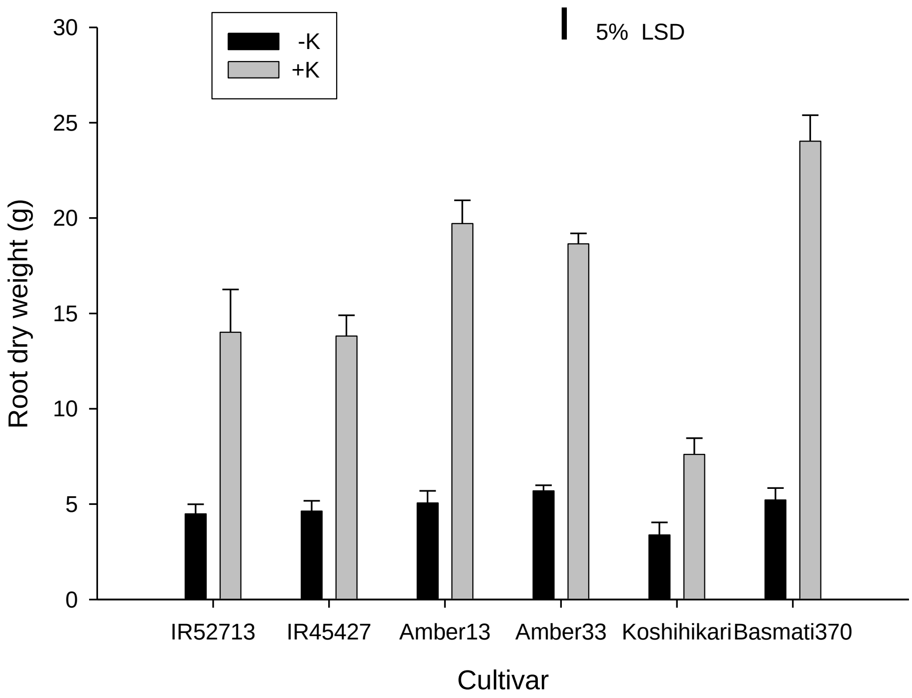


Figure 3.17 Effect of K application (no potassium vs 200 mg K/kg) on root dry weight (g/pot) of six rice (*Oryza sativa*) cultivars grown for 84 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with ± standard errors indicated by bars.

3.4.1.5 **Effect of K on plant stem diameter**

Potassium fertiliser again increased ($P < 0.05$) stem diameters in all cultivars (Figures 3.18 and 3.19). Koshihikari had the narrowest stems and also showed the smallest increase in stem thickness in response to K application. The Amber cultivars showed the greatest increase in stem thickness in response to K application. Stem diameters of plants were not significantly ($P \geq 0.236$) affected by the interaction between WAS (10 – 13), cultivar and K rate in this experiment (Appendix 3.5).

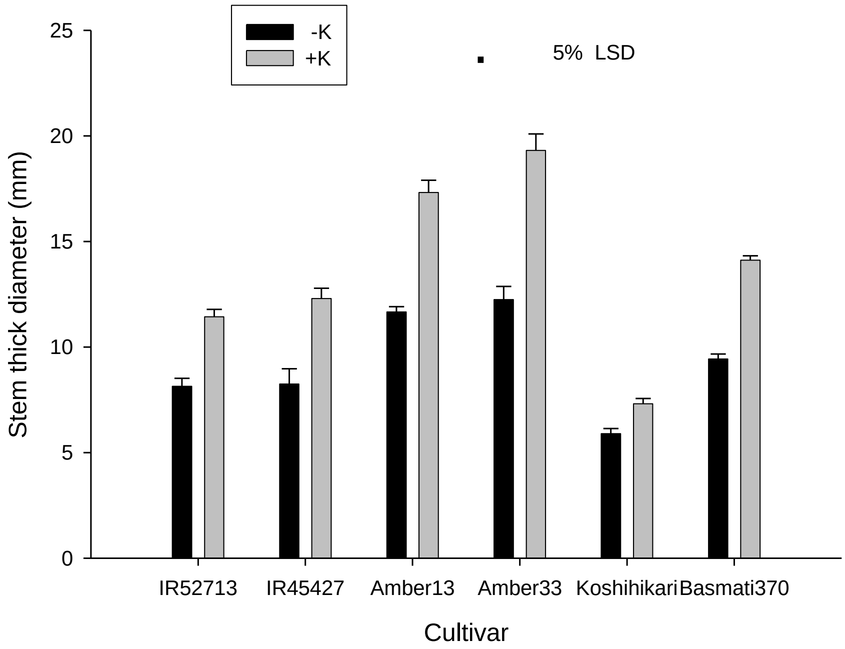


Figure 3.18 Effect of K application (no potassium vs 200 mg K/kg) on thick stem diameter (mm) of six rice (*Oryza sativa*) cultivars grown for 70 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with ± standard errors indicated by bars.

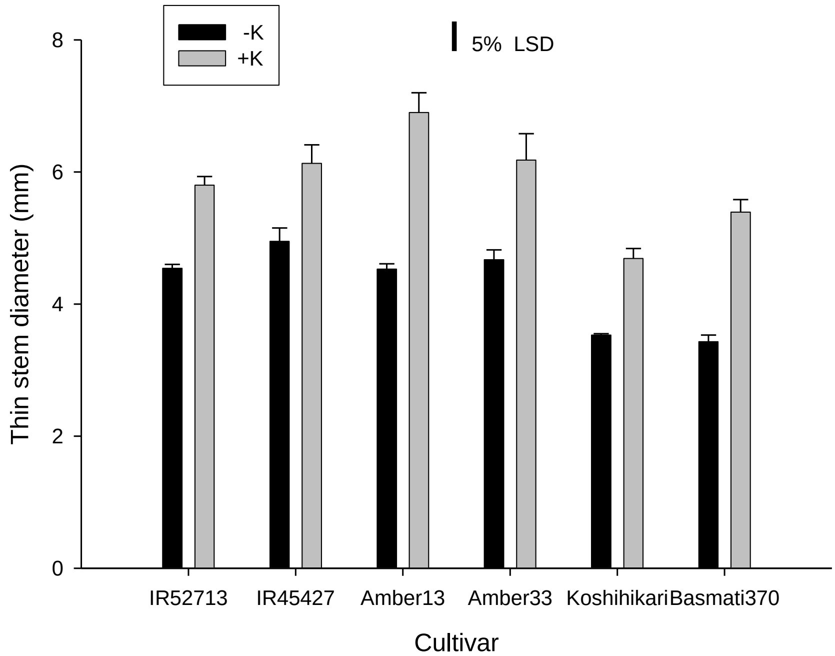


Figure 3.19 Effect of K application (no potassium vs 200 mg K/kg) on thin stem diameter of six rice (*Oryza sativa*) cultivars grown for 70 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with ± standard errors indicated by bars.

3.4.1.6 **Effect of K on plant stem strength**

Potassium application again increased (P < 0.01) both lower and upper stem strength in all cultivars (Figure 3.20 and 3.21). There were significant interactions between K application and cultivar in stem strength; the magnitude of this increase was significantly greater for IR45427 and least in Koshihikari and Amber33 (in upper stem strength only).

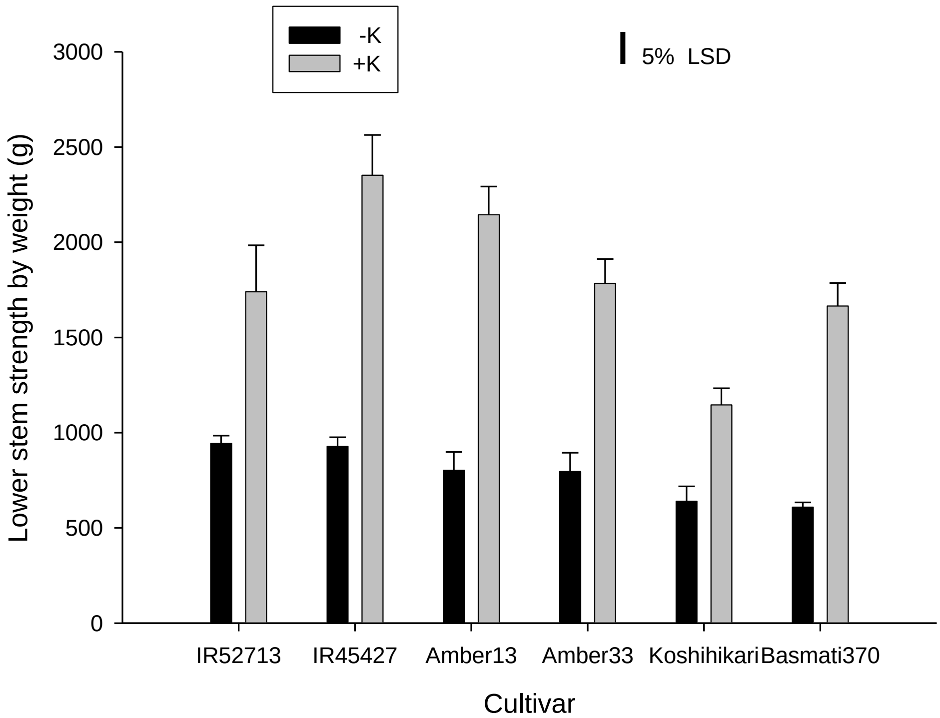


Figure 3.20 Effect of K application (no potassium vs 200 mg K/kg) on stem strength down by weight (g) of six rice (*Oryza sativa*) cultivars grown for 84 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with standard errors indicated by bars.

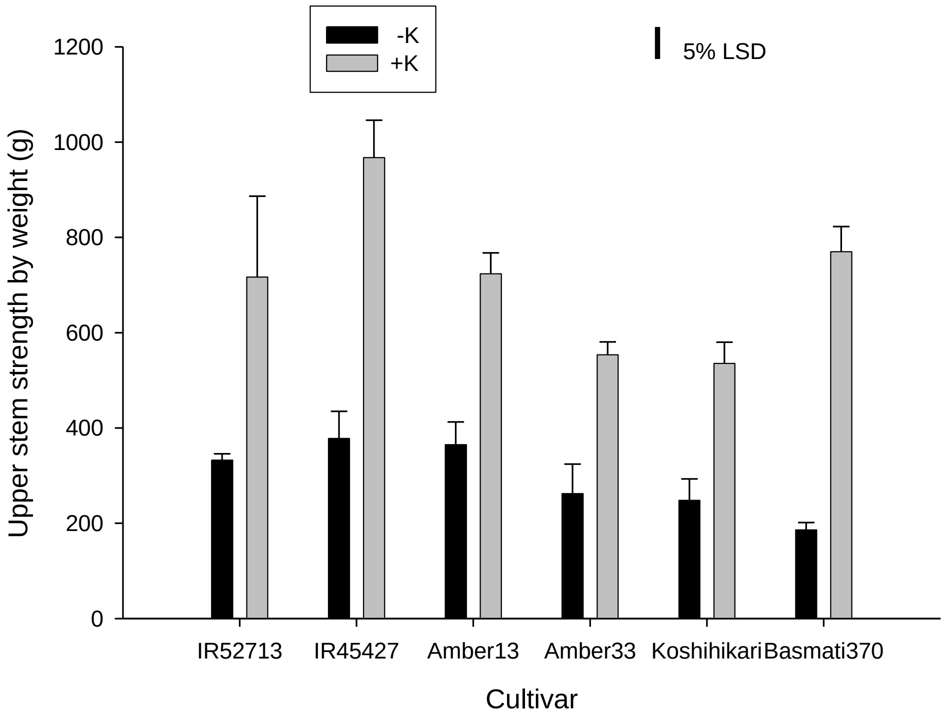


Figure 3.21 Effect of K application (no potassium vs 200 mg K/kg) on stem strength up by weight (g) of six rice (*Oryza sativa*) cultivars grown for 84 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with ± standard errors indicated by bars.

3.4.1.7 Effect of K on K concentrations in leaf, stem and root

Effect of K application on K concentrations in leaves, stem and root are presented in Table 3.3. Plant analysis results indicated that increasing K level from 0 to 200 mg/kg significantly ($P < 0.05$) increased the concentration of K in leaves, stem and root. The concentrations of K in leaves showed increases of 288, 250, 176, 146, 68 and 67% over the control plants for IR45427, Koshihikari, IR52713, Basmati370, Amber33 and Amber13, respectively.

In addition, the K concentrations in stem material showed an increase of 414, 358, 183, 65, 63 and 57% over the control plants for IR45427, Koshihikari, Amber13, IR52713, Amber33 and Basmati370 respectively.

In root material, the concentrations of K also showed increases of 131, 122, 85, 83, 53 and 50% over control plants for Koshihikari, Amber13, IR45427, Amber33, Basmati370 and IR52713, respectively. In general, there were low levels of K retained in roots compared with stem and leaf material.

Table 3.3 Effect of K application (no potassium vs 200 mg K/kg) on K conc. (%) in leaves of six rice (*Oryza sativa*) cultivars grown for 84 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with ± standard errors of the means.

Cultivar	K status	Leaves K (%)	Stem K (%)	Root K (%)	K uptake (Leaf+Root) (mg/pot)
IR52713	-K	0.21±0.027	0.17±0.006	0.16±0.01	48±50
IR52713	+K	0.58±0.065	0.28±0.017	0.24±0.01	234±12
IR45427	-K	0.16±0.010	0.14±0.018	0.13±0.007	31±20
IR45427	+K	0.62±0.034	0.72±0.075	0.24±0.03	197±5.7
Amber13	-K	0.24±0.022	0.53±0.048	0.18±0.006	46±20
Amber13	+K	0.40±0.037	1.50±0.110	0.40±0.04	208±4.5
Amber33	-K	0.28±0.012	0.80±0.050	0.18±0.005	54±3.8
Amber33	+K	0.47±0.024	1.30±0.235	0.33±0.03	213±7.5
Koshihikari	-K	0.16±0.013	0.12±0.030	0.13±0.01	25±3.7
Koshihikari	+K	0.56±0.101	0.55±0.073	0.30±0.01	171±28
Basmati370	-K	0.24±0.014	0.53±0.090	0.17±0.01	46±30
Basmati370	+K	0.59±0.017	0.83±0.234	0.26±0.03	274±2.9
LSD (0.05)		**0.08**	**0.23**	**0.04**	**19.67**

There were significant ($P < 0.05$) interactions in plant K uptake (Table 3.3) and in the plant K/total available K ratio (Figure 3.22) between cultivar and K fertilisation at 200 mg/kg. For the plant K/total available K ratio, IR52713, IR45427, Amber13, Amber33, Koshihikari, and Basmati370 showed an increase of 48, 92, 38, 19, 107 and 81%, respectively over the control (zero K treatment). All six cultivars accumulated increasing K amounts in their shoots and roots at equal K level (200 mg/kg). Koshihikari accumulated the highest amount of K compared to the other cultivars. Furthermore, in this experiment, nearly the same amount of K accumulated in both semi-dwarf cultivars (IR45427 and IR52713). However, both standard and tall cultivars (Amber13 and Amber33) accumulated less K in their tissue.

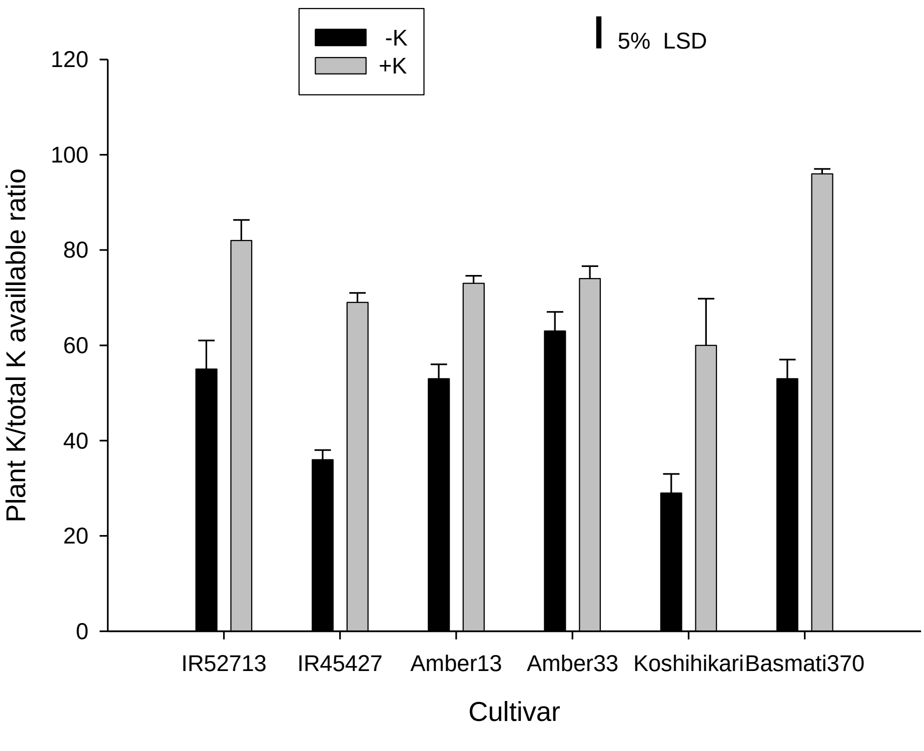


Figure 3.22 Plant K/soil K ratio (plant K/applied K) of six rice (*Oryza sativa*) cultivars in summer experiments, grown for 84 days in a glasshouse on a K responsive Black Vertosol. Values are the mean of 4 replicates with ± standard error indicated by bars.

3.5 Discussion

These two experiments were conducted using an Australian soil low in available K and which had previously grown crops which were K deficient. As would be expected, Figure 3.1 shows K deficiency in rice plants; the symptoms of K deficiency appeared first on the oldest leaves (Section 2.3.13). However, as K rate increased leaf-K concentration increased significantly by 105 – 141% in the winter experiment and by 67 – 288% in the summer experiment compared to control treatment. Potassium deficiency symptoms occurred only when rice received no K fertiliser.

A field experiment carried out in Iraq has also shown K deficiencies (Chapter 6). It remains to be seen, when further work in this area is carried out in Iraq, whether similar low K levels are common in rice growing regions and whether growth and lodging effects associated with low K levels can be duplicated under field conditions. This has generally been attributed to the mobility of K within the rice plant, thus older leaves are scavenged for the K needed by younger leaves (Dunn and Stevens 2004).

Lodging can occur at three places in rice plants; from the base of the plant in early growth, at mid-tillering and as a result of heavy panicles. In these experiments lodging occurred primarily from the base, due to poor root growth in the absence of K (Figure3.2).

Plants were harvested at panicle initiation and hence lodging at the final stage was not investigated. Lodging is difficult to quantify directly in a glasshouse experiment, where conditions such as lack of wind differ from those in the field. For this reason susceptibility to lodging was assessed here from several proxies, namely upper and lower stem strength, and thick and thin stem diameter. Application of N promotes vegetative growth and plant height, and regular applications of N without supplemental K are not conducive to strong plant stands. The lack of K application in Iraq is a historical anomaly based on recommendations from the British Soil Survey group in the mid 1950's who correctly identified K application was not required for rice due to high soil K reserves. However, 60 years of continuous rice production without K application would have reduced soil K supply considerably; hence the yield losses currently observed across important Iraqi rice production areas. These experiments demonstrated that, under low soil K levels, the application of K significantly increased shoot (120 – 140%) and root (80 – 300%) dry matter production, thus reducing lodging incidence thus reducing lodging incidence in the winter experiment particularly. Another potential alternative to improve lodging resistance may be deeper planting depths to limit basal root lodging at the soil surface.

In both the present experiments, all rice cultivars tillered well when K fertiliser was applied. Tillering is important in determining the number of panicles per plant, which determines potential grain yield. Similarly, Fageria (2007) reported that tillering was positively related to grain yield at all the growth stages, however, the highest correlation over three years of experimentation was obtained with tillering at the panicle initiation stage.

This effect of K in improved tiller numbers, which was generally associated with enhanced nutrient uptake and transportation, especially K, was consistent with the results of Bahmaniar and Ranjbar (2007b), Bohra and Doerrffling (1993) and Yang *et al.* (2004). Although tillering increased in this K responsive trial, Surendran (2005) observed a 58%

increase in tillering in a clay soil with already high K status following a small addition of 42 kg/ha rate of K at both the tillering and panicle initiation stages.

In experiment 1 under high N conditions, the standard cultivar (Amber13), which is very similar in growth habit and provenance to the Iraqi rice cultivar Amber33, was more prone to lodging than semi-dwarf cultivars (IR45427 and IR52317) due to N being involved in vegetative growth, which will result in tall and weak stems. However, in experiment 2, the summer experiment, all cultivars (except IR45427) recorded higher values of thick stem diameter. This is probably because the summer grown rice grew faster and produced more dry weight than the winter rice, due to the long photoperiod during the summer season (Talukdar and Beka 2005).

In Iraq, farmers commonly apply a high rate of N (~300 kg N/ha) with the aim of increasing rice grain yields. Whilst N enhances growth and tillering, it may limit rice productivity when applied in excess, via increased lodging, which is more pronounced with the tall cultivars like Amber33 (Bahmaniar and Ranjbar 2007).

Root extension is another component of vegetative development. The application of K promotes the development of strong root systems (Section 5.2.6) and an adequate root architecture needed for water and nutrient uptake as well as increased resistance to lodging. The beneficial effects were shown in the establishment of larger root system and also in increased stem strength, both of which may be important contributors to reducing lodging and increasing production of rice under Iraqi soil conditions.

In these experiments plant height of the rice cultivars responded positively to K addition. Responses to K application especially when complemented with N have been attributed to synergistic effect of K on N uptake and in maintaining the activity of K during the late vegetative stage. These results agree with those reported by Bahmaniar and Ranjbar (2007a), Bohra and Doerffling (1993) and Surendran (2005). Enhancement of plant height can prompt competition for light resulting in further increases in plant heights. This result is consistent with the results of many investigators (Bohra and Doerffling 1993; Gent 1995; Surendran 2005). A similar trend was observed by Salim (2002) in a solution culture experiment; a K level of 200 mg/L increased rice plant height (IR2035) by 37% and the tiller number by 10% at 50 DAT.

Shoot DW and RDW of rice significantly increased by applying 200 mg K/kg. Potassium increased plant biomass due to its effect on photosynthetic activities in the leaves and to increases in the transport of carbohydrates from leaves to roots for respiration and other physiological process including root growth. Similarly, Bohra and Doerffling (1993) and Wu *et al.* (2009) found that applied K resulted in a progressive increase in SDW and RDW.

The length and stiffness of rice stems and the level of tillering are important in determining the N responsiveness of a rice plant. Tall and weak-strawed cultivars lodge early and severely at high N levels. Under high N conditions, significant increases in plant height and tiller numbers in response to K application were observed (Figures 3.5, 3.6, 3.14 and 3.15). This is probably due to enhanced availability of N which increases leaf area resulting in higher photo assimilate production and this resulted in more dry matter accumulation (Figures 3.7 and 3.8). In contrast, rice cultivars succumb to lodging when N was applied at high rate in the absence of applied K (Figure 3.4). This experiment demonstrated that application of K fertiliser can reduce the incidence of lodging in the presence of high N supply (~300 kg N/ha).

Adequate stem diameter plays an important role in providing mechanical support to plants; in rice, this morphological parameter is instrumental in increasing resistance to lodging (Mulder 1954). The present results showed that the thickest and thinnest diameters of stems increased with K addition compared to no K plants. This result is supported by the earlier findings of Kant and Kafkafi (2002), who also found increased plant susceptibility to lodging where K was not applied, due to the reduction in the stem diameter, making the plants more susceptible to lodging. Mulder (1954) suggested that the stems of K deficient plants formed thin and poorly lignified cell walls (associated with reduced sclerenchyma fiber and woody parenchyma cell development) and that this reduced stem diameter. Kashiwagi and Ishimaru (2004) also reported that lower contents of accumulated carbohydrates in rice stems, resulting in reduced stem diameter, making the plant susceptible to lodging. Potassium has been reported to increase stem diameter and the likely cell-wall thickness in rice (Brady and Weil 2002; Kumar 2009; Mengel and Kirkby 1982) and in corn (Kant and Kafkafi 2002). In these experiments, the application of K significantly increased stem diameter but the Iraqi cultivar Amber33 recorded the greatest relative increase in thick stem diameter in response to K application (see Figure 3.18). Thus, even in relatively tall cultivars such as the Iraqi cultivar Amber33, increasing stem diameter could have a profound effect in overcoming lodging.

This study showed that K may play an important role in increasing the breaking strength of the basal stem in all selected cultivars (see Figures 3.11, 3.12, 3.20 and 3.21). However, this effect was more pronounced in the semi-dwarf lines. It is well known that K enhances starch accumulation in cell walls, which has been postulated to increase the hardiness of lower part of rice stem, hence enhancing lodging resistance (Kashiwagi *et al.* 2005; Stevens *et al.* 2001). In experiment 1, the short cultivars (IR52713 and IR45427) showed more resistance to applied weights compared to the breaking weight of the standard cultivar (Amber13). The results from this experiment have shown that of the cultivars examined within this thesis, Amber13 was the most sensitive to lodging under conditions of high N and low K, due either to stem strength or basal lodging effects. However, the breaking weights for all cultivars were higher and the stems were thicker and stronger (Figures 3. 9, 3.10, 3.18 and 3.19) in experiment 2 (summer) than during the winter experiment due to the faster growth, and thicker diameter of rice plants in summer season than during winter. The strength in stem is also important in relation to its stability against lodging (Talukdar and Beka 2005).

As would be expected using this low K soil, in both experiments K application increased the K concentrations in leaves, stems and roots (see Tables 3.2 and 3.3). Tissue K concentrations are indicators that can be used to determine the nutritional requirements of plants when approaching critical values. The variation in the concentration of K in tissue parts such as leaves, stem and root within rice also highlight the importance of assessing their significance to rice yield. Potassium fertilisation markedly increased the root K concentration of rice in both experiments, despite the presence of root washing that would tend to lower the total amount of K observed in the roots. It also tended to enhance K content in leaves and stem of all cultivars. This trend was also noted by Aide and Picker (1996). The K concentration of leaves and stems varied during reproductive growth stage among the rice cultivars. The leaves had higher K than the stems in short cultivars (IR52713 and IR45427), indicating that the leaves might have accumulated more K during the early development period. Conversely, in Amber13, K concentration of leaves was lower than that of stems. Depending on the cultivar, it is possible that K is exported from leaves to the panicles through the stems during the developmental growth period leading to higher stem K concentration (Chen *et al.* 1980) or as the plant grows and dry matter increases, soil K becomes depleted, causing internal redistribution of K within the plant parts (Dobermann and Cassman 1996).

In both experiments K application increased markedly the concentrations of K in stems and leaves as well as roots. However, the concentrations in the cultivars used in the summer experiment were less than the concentrations of those in winter experiment. The stem dry weights of the cultivars grown during summer season were higher than those in winter season (Figures 3.7 and 3.16); this drop in K concentration is probably due to a growth dilution effect. An increase in plant biomass decreases K concentrations in plant tissues under limited K conditions. Under a limited nutrient supply, there is maximum dilution of the nutrient in the plant, conversely, when the supply of a nutrient is large and growth is not limited by uptake, the internal nutrient concentration is high, and there is maximum accumulation. In this situation, growth is limited by other factors (Dobermann and Cassman 1996).

Rice plants vary in their ability to take up K depending on several factors including soil, plant, growth stage and management practises, as well as the growing season. For example, by week 14 after transplanting, some of the cultivars such as Koshihikari and IR45427 had already attained early maturity (at the end of reproductive stage), while others were still at the early reproductive stage due to differences in growth duration among selected rice cultivars. The concentrations of K in leaves and stems during the vegetative stage were fairly uniform. According to Slaton *et al.* (2004), these concentrations follow trends similar to the K concentration in soil water (under flooded conditions) at the first few weeks after flooding with reductions at the early reproductive stage due to the dilution effect on plant K.

This study showed that the application of K reduced lodging under high N (Figure 3.4) and increased tiller number, height of plant, shoot and root dry matters, stem diameter and stem strength all changed in response to that application. Further research is required to isolate the specific parameters responsible for the reduced lodging. Lodging would be reduced with any decrease in plant height. There were also important interaction effects with K on the individual cultivars used in these experiments, e.g. in winter experiment, K application increased number of tillers in all cultivars, but IR52713 had more tillers than other cultivars (Figure 3.5). In addition, in summer experiment, K also caused increase in plant height for all cultivars, but Basmati370 exceeded 97 cm (Figure 3.15). This interaction reflects the significant and positive cultivars response to K addition under soils testing low in available K.

Plant characteristics such as tissue K concentration, number of tillers, height, thick and thin stem diameter, shoot and root DW and lower and upper stem strength were significantly affected by cultivar in both experiments. However, interaction between cultivar and K application varied according to the season the experiment was undertaken, with only root dry weight and tissue K concentration consistently interacting (Appendix 3.6). The winter trial observed interactions between root and root K factors, tiller number, and upper stem strength. In summer experiment there were cultivar effects on all above mentioned characteristics but K concentration in leaves, also cultivar by K interaction affected all characteristics except tiller number (Appendix 3.6). Application of K improved plant morphological characteristics and application of N in the absence of K has adverse effects on plant growth which is less in shorter statured cultivars. Additions of N to Iraqi cultivar (Amber33) in the absence of K increase vegetative growth and susceptibility to lodging.

In addition to enhanced rice growth parameters due to the addition of K, the positive effect of K on decreasing probable lodging incidence was likely with improved root growth and hence better anchorage for the rice plant.

3.6 Conclusion

This glasshouse study suggests that lodging could be reduced following K application at 200 kg/ha in standard rice cultivars similar to those grown in Iraq, including the popular Amber33. There were, however, major differences in which cultivars responded to applied K fertiliser. Using a range of cultivars it would be useful to apply test strip trials of K application under field conditions to assess the value of K fertiliser in low soil K regions in the Iraqi rice production areas.

Such experimental work should also be conducted using a range of K fertiliser levels to determine optimum field application rates on soils with differing levels of variable soil K. Some preliminary field work is reported in Chapter 6.

CHAPTER 4: **POTASSIUM AND RICE UNDER HIGH SALINE CONDITIONS**

4.1 Introduction

4.1.1 The impact of salinity on cation concentrations and rice growth

Salinity affects the growth and production of rice worldwide (Yeo and Flowers 1986). There are many effects of salinity on rice. In recent years, soil salinity in Iraq has reduced rice production by 40 – 50% (IRIN 2010). One effect of salinity on irrigated summer crops is related to the cation composition of the soil water and the effect this has on the availability of K (Horie *et al*. 2007). This chapter focuses on salinity effects that may impact the uptake and availability of K. These include changing ion concentrations in soil solution and its effect on seedling growth under flooded conditions and following application of K, in selected rice cultivars. This chapter investigates impact of K fertilization with and without the constraint of salinity on rice establishment and growth under the high N and P application rates prevalent in Iraqi production.

4.1.2 Potassium activity ratio

The optimum K level in the soil solution varies between 10 – 60 µM, depending on the crop, soil texture, general fertility level and soil moisture supply (Gowariker *et al.* 2009). The availability of soil K for crop uptake is also influenced by the presence of other cations, such as Ca^{2+} and Mg^{2+}. In salt affected soils, Na^+ ions may also influence the uptake of soil K by the crop, due to antagonistic interactions between Na^+ and K^+ (Bernstein 1975; Endris and Mohammed 2007). The activity ratio of K in soil solution is given by:

$$AR^K = aK/a(Ca+Mg)^{0.5}$$

Where a^K is the activity of K ion and a(Ca+ Mg) the activity of Ca and Mg cations. Activity ratio is an intensity (I) factor (Munn and McLean 1979). According to Beckett (1964), the intensity (I) of K in a soil at equilibrium with its soil solution might best be defined by (AR^K) of the soil solution. Muchena (1984) observed strong correlations between AR^K and K uptake in sorghum (*Sorghum bicolor* L.) plants. Other researchers have also observed relationships between AR^K and the availability of K to plants (Gowariker *et al.* 2009; Sumner and Marques 1966). However, AR^K is not a measure of the size of the labile K pool in soil, as soils with similar AR^K values can have considerably different exchangeable K concentrations (Sumner 1965). As a measure of K intensity in solution, it is affected by both labile K, and the rate of fixed K release into solution (Gowariker *et al.* 2009).

With this in view, a glasshouse experiment was conducted to evaluate the effects of K application on cation concentrations, K activity ratio and the growth of rice seedlings with flooding under both saline and non-saline conditions.

4.2 Methods

A glasshouse experiment was conducted at the University of New England (UNE) in March 2010. Three rice cultivars of different susceptibility to salinity, namely; Koshihikari (salt-sensitive), Amber33 and IR45427 (salt-tolerant) (Abdelgadir *et al.* 2005; Lee *et al.* 2003) were used in this experiment. The three rice cultivars were used with four K treatments including no fertiliser, 200 or 400 mg/kg applied at establishment and 200 mg/kg applied in a split application consisting of 50 mg/kg at establishment, 75 mg/kg 40 DAT (early tillering), and 75 mg/kg applied 65 DAT (late tillering). The plants were subjected to two salinity levels non saline (0.8 dS/m) and saline (7 dS/m). The Vertosol described in Table 3.1 was used in the experiment.

Soil solutions were extracted *in situ* three times during April and May from a soil depth 2 – 4 cm for EC, pH and major cations (K^+, Na^+, Ca^{2+} and Mg^{2+}) measurements from all treatments except the 400 mg/kg treatment.

Rice seeds of IR45427 and Koshihikari were supplied by the Yanco Agricultural Institute, NSW, Australia. Amber33 was supplied by the Rice Research Station, Iraq. The seeds of three rice cultivars were germinated on 18th March 2010 at 29˚C on moist filter paper in a plant growth cabinet without nutrients and were watered with de-ionised water only. Similar sized seedlings seven days old were transferred into treated soil in lined 150 mm plastic pots, 150 mm deep. Each pot contained 1 kg of Vertosol, with two plants.

Each cultivar was grown on a separate bench and surrounded by plants of the same cultivar on all sides to provide a close approximation to canopy and light structures that could be observed in the field; and laid out in a completely randomised design (CRD) with three replications under uniform greenhouse conditions (Figure 4.1). A completely randomised design incorporating all cultivars was not possible due to the variation in plant heights between cultivars. Average mean temperature during the growth trial was 30/25°C day/night. Rice pots were flooded 20 DAT to a depth of 3 to 5 cm of standing water and remained flooded during the crop growth period. Watering was stopped; and the experiment was finished on July 2, 2010.

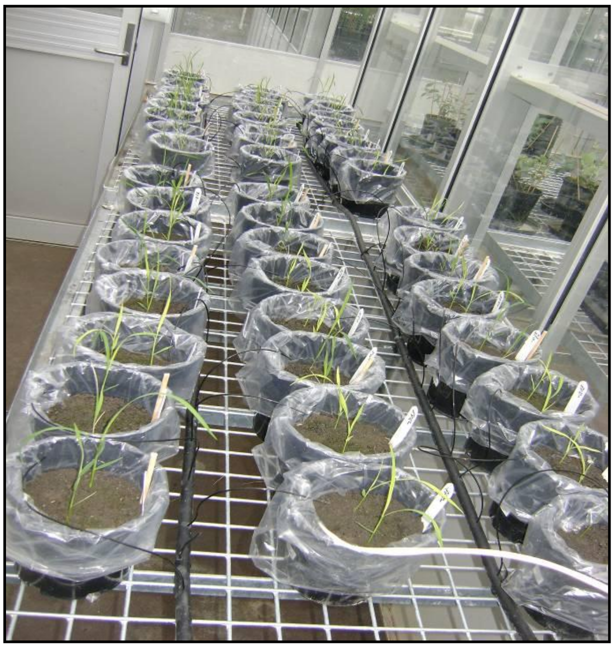


Figure 4.1 Glasshouse experiment, located at UNE, Armidale, April, 2010.

4.2.1 Fertiliser applications

Potassium was applied as potassium chloride (muriate of potash, 50%K) in solution to achieve the three rates of K applied. Nitrogen as urea (46% N) was applied at 100 mg/kg soil at transplant, 50 mg/kg 30 DAT and 50 mg/kg 44 DAT. A basal application of P was applied to all pots at a rate of 50 mg/kg soil as calcium tetra hydrogen di-orthophosphate ($Ca(H_2PO_4)_2$) (24%P) and S as gypsum (15% S) at 20 mg/kg.

4.2.2 Soil electrical conductivity

Two levels of soil salinity 0.8 dS/m (control) and 6 – 8 dS/m were used in this experiment. The relationship was determined in a laboratory by using a mixture of equal masses of $MgSO_4.7H_2O$ and NaCl. The range of 6 – 8 dS/m was created by adding 0.12 g of mixed salts to 50 g soil (Figure 4.2).

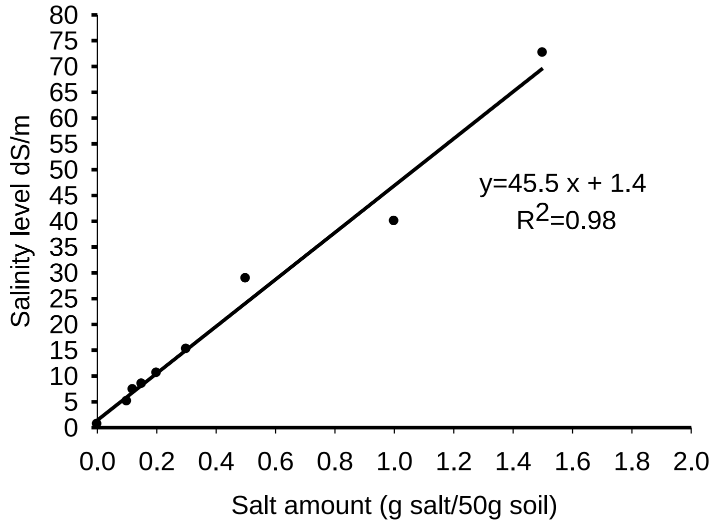


Figure 4.2 Determinations of in situ soil solution EC (dS/m) of Vertosol.

4.2.3 Potassium activity ratio

Potassium activity ratio (AR^K) in the soil solution was determined from the activities of K, Ca and Mg in the equilibrium solution; and calculated using the following formula described by Kopittke and Menzies (2005).

$$AR^K = aK/\ (aCa+aMg)^{0.5}$$

4.2.4 Extracted Soil Solution

The soil solution from the Amber33 cultivar was collected to measure cations (K^+, Na^+, Ca^{2+} and Mg^{2+}) using hollow-fibre solution samplers described by Menzies and Guppy (2000). In brief, soil solution is drawn through hollow, polyacrylonitrile fiber filters under vacuum applied from an evacuated blood sampling vial at low tension, creating a syphon effect. Hollow-fiber filter elements can be used to extract soil solution without destructive sampling and are considered to remove soil solution *in situ* from water in the large, plant available pores.

Hollow-fiber soil solution extractors were constructed from an Asahi Chemical Industry Co AHP-2010 model biofilter following removal of fibres. One end of the fiber was sealed with nylon fishing line (0.8 mm OD) secured with Supa-glue (isocyanurate) while the other was inserted 5mm into a 10mm piece of Choice Analytical PVC pump tubing (1.42 mm ID) and secured with Supa-glue. In the other end of the pump tubing a 10 cm length of PTFE#20 tubing was inserted 5mm and secured with Supa-glue. A 20G vacutainer needle was inserted into the end. The soil solution samplers were buried in pots; the sealed end 4cm deep and extracting end 2cm deep. When connected to a 10 mL vacutainer the vacuum created caused 8-10mL of soil solution to flow into the collection tube (Figure 4.3).

Solution EC and pH were determined directly following extraction. This was carried out using a TPS labCHEM, conductivity-TDS-Temperature Meter with calibration standard 2.76 mS/cm for EC and a TPS 901-CP, conductivity-TDS-pH-mv meter with pH 4, 6.88 and 10.01 as calibration buffers for pH. Major cations (K^+, Na^+, Ca^{2+} and Mg^{2+}) were determined by inductively coupled plasma atomic emission spectroscopy (ICPAES).

Figure 4.3 Hollow-fiber soil solution extractor.

4.2.5 Calculation of cumulative mortality

Dead plants were counted every three days from transplanting until 22 DAT. Percent mortality was calculated using the final cumulative mortality counts. After this date mortality remained stable.

4.2.6 Statistical analysis

The data collected from this experiment were statistically analysed using analysis of variance (ANOVA) using R (R Development Core Team 2009) and the differences among the treatments means were compared by employing LSD at 5% level of probability.

4.3 Results

4.3.1 Soil EC and pH under flooded conditions

Application of salt increased the salinity of the soil solution by 300% ($P < 0.001$) (Table 4.1). The interaction between salinity and time was significant ($P < 0.01$), the EC fell by 60% when K was applied in a split manner over time, whilst an upfront application of K resulted in a 30% decrease in salinity with time (Table 4.1). There were small but significant changes ($P < 0.001$) in pH during the three sampling times, however pH remained between 6.3 and 7 (Table 4.1).

Table 4.1 Change in electrical conductivity (EC) and pH of the soil solution following application of 200 mg/kg of K to a Black Vertosol soil growing Amber33 rice (*Oryza sativa*) during the first 46 days of growth under saline and non-saline conditions. Values are the mean of 3 replicates with ± standard errors of the means.

Treatment	Application strategy	14 DAT	27 DAT	47 DAT	14 DAT	27 DAT	47 DAT
		EC (dS/m)			pH		
Control (Non saline/ No K)		0.7±0.2	0.7±0.1	0.5±0.2	6.55±0.2	6.61±0.1	6.95±0.1
Saline	Split	3.0±0.1	2.4±0.5	1.3±0.3	6.49±0.2	6.60±0.1	6.66±0.1
Non saline	Split	0.9±0.1	0.7±0.1	0.6±0.2	6.54±0.1	6.77±0.1	7±0.2
Saline	Upfront	3.3±0.4	2.8±0.7	2.3±0.5	6.39±0.1	6.54±0.2	6.81±0.1
Non saline	Upfront	1.4±0.1	1.2±0.2	1.1±0.1	6.30±0.1	6.6±0.1	6.71±0.1
LSD (0.05)		**0.29**			**0.10**		

4.3.2 Effects of K addition on cation concentrations

As expected higher cation concentrations were found in the high EC soils. At 6 – 8 dS/m, Na^{+} was the highest in soil solution followed by Ca^{2+}, Mg^{2+} and K^{+}. The concentrations of Ca^{2+} and Mg^{2+} ions in soil solution were strongly influenced ($P < 0.001$) by salinity (Table 4.2a and b). Increasing salinity from 0.8 to ~3.0 dS/m resulted in release of these cations to the soil solution. An increase from 75 µg/ml (for Ca) and 47 µg/ml (for Mg) to 188 µg/ml and 150 µg/ml, respectively occurred when split application was used and from 97 µg/ml (for Ca) and 60 µg/ml (for Mg) to 240 and 186 µg/ml, respectively when upfront application was used during the first time of sampling (14 DAT). A similar trend was observed during the sampling times 27 DAT and 47 DAT. In the same way, Ca^{2+} and Mg^{2+} concentrations in soil solution were also strongly enhanced by K application strategy. The concentration of either cation Ca^{2+} or Mg^{2+} was significantly higher ($P= 0.018$ and 0.029, respectively) when K was applied as a single dose before planting (upfront) than when the application was split. The time of sampling also had a strong effect (P= 0.014 and 0.009 respectively), on the concentration of Ca^{2+} and Mg^{2+}, decreasing over time (Table 4.2). As expected, large increases ($P < 0.001$) in Na^{+} and Mg^{2+} concentrations occurred with increased levels of NaCl and $MgSO_4$ (Table 4.2d). Similarly, K^{+} ions in soil solution was strongly increased ($P < 0.001$) by application strategies (Table 4.2c).

Table 4.2 Effects of salinity 0.8 – ~3.0 dS/m, application strategy of 200 mg/kg of K and sampling time on (a) Ca^{2+} , (b) Mg^{2+} , (c) K^{+} and (d) Na^{+} concentrations in soil solution under rice (*Oryza sativa* cv Amber33) growing in a Vertosol. Values are the mean of 3 replicates with ± standard errors of the means.

a

Treatment	Application strategy	14 DAT Ca (µg/ml)	27 DAT Ca (ug/ml)	47 DAT Ca (ug/ml)
Control		55±17	46±13	25±8
Saline	Split	188±18	164±40	62±13
Non saline	Split	75±11	52±11	64±26
Saline	Upfront	240±9	188±59	150±33
Non saline	Upfront	97±29	91±19	78±7
LSD (0.05)		**33.1**	**61.5**	**37.0**

b

Treatment	Application strategy	14 DAT Mg (µg/ml)	27 DAT Mg (µg/ml)	47 DAT Mg (µg/ml)
Control		34±10	33±7	17±5
Saline	Split	149±10	120±30	46±11
Non saline	Split	47±7	33±7	43±18
Saline	Upfront	186±5	138±46	106±26
Non saline	Upfront	60±21	60±14	53±5
LSD (0.05)		**21.4**	**46.9**	**27.7**

c

Treatment	Application Strategy	14 DAT K (µg/ml)	27 DAT K (µg/ml)	47 DAT K (µg/ml)
Control		1.3±0.3	5.0±1.3	3.0±0.8
Saline	Split	8.4±0.6	5.0±1.0	13.0±5.1
Non saline	Split	8.9±1.4	4.7±0.5	19.5±2.3
Saline	Upfront	29.1±7.9	17.2±3.0	16.5±2.0
Non saline	Upfront	26.4±8.2	20.2±5.3	12.8±3.3
LSD (0.05)		**9.4**	**5.1**	**5.6**

d

Treatment	Application Strategy	14 DAT Na (µg/ml)	27 DAT Na (µg/ml)	47 DAT Na (µg/ml)
Control		14±2	22±8	9±3
Saline	Split	192±21	154±21	65±11
Non saline	Split	17±2	12±2	15±5
Saline	Upfront	215±26	165±45	126±27
Non saline	Upfront	17±2	16±3	17±0.2
LSD (0.05)		**27.5**	**41**	**24**

The ratio of Na^+/K^+ in soil solution was significantly increased ($P < 0.05$) with increasing salinity at different sampling time intervals (Table 4.3). Both application strategies of K, split and upfront applications decreased Na^+/K^+ ratios to 6.8 and 7.5 respectively at the third sampling time, despite the increase in salinity level.

Table 4.3 Solution potassium (K) activity and ratio of Na:K in early season soil solution of a Vertosol growing rice (*Oryza sativa* cv Amber33) in the absence (Control) and presence of 200 mg/kg of K. Values are the mean of 3 replicates ± standard errors of the means.

Treatment	Application strategy	Potassium activity ratio (AR^K mmol/kg)$^{0.5}$			Na:K ratio		
		14 DAT	27 DAT	47 DAT	14 DAT	27 DAT	47 DAT
Control		0.03±0.01	0.13±0.05	0.17±0.08	14±4	4±1	4±2
Saline	Split	0.06±0.01	0.04±0.004	0.25±0.08	23±3	32±2	7±3
Non saline	Split	0.15±0.04	0.11±0.02	0.52±0.2	nd*	nd	nd
Saline	Upfront	0.16±0.05	0.13±0.03	0.15±0.02	9±3	10±2	8±1
Non saline	Upfront	0.32±0.09	0.26±0.04	0.19±0.04	nd	nd	nd
LSD (0.05)		**0.08**	**0.06**	**NS**	**4.5**	**2**	**3.2**

*nd – not determined

4.3.3 Potassium activity ratio (AR^K)

Potassium application significantly affected AR^K ($P < 0.05$) up to 27 DAT. However, no significant difference was observed 47 DAT. Similarly, AR^K was significantly affected ($P < 0.05$) by salinity at the first and second times only. Potassium activity was highest in non-saline soils treated with K (Table 4.3). However, AR^K was lowest in saline (EC=6 – 8 dS/m) treatments, and ranged between 0.13 – 0.16 and 0.04 – 0.25 in both upfront and split applications, respectively (Table 4.3 and Figure 4.4).

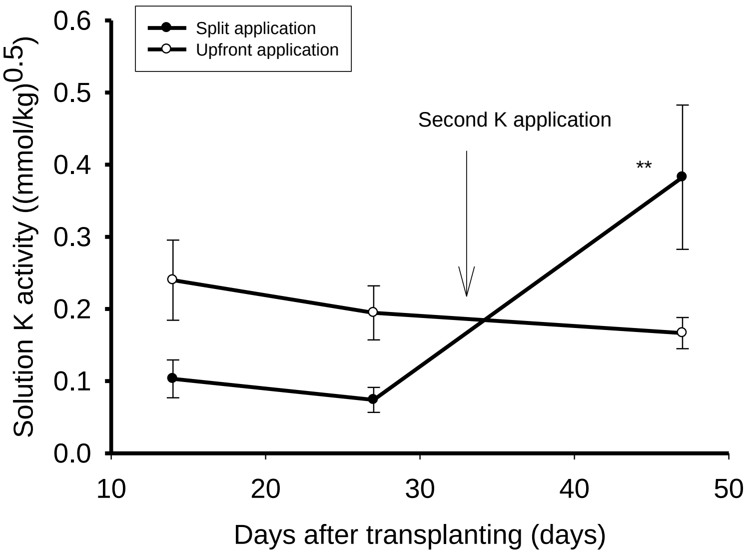


Figure 4.4 The change in soil solution K activity ratio during the first 7 weeks of growth of rice (*Oryza sativa* cv Amber33) following either initial application of 200 mg K/kg or a split application of K with 50 mg K/kg applied initially and a further 75 mg K/kg applied in the 4th week of growth. Values are the mean of 3 replicates averaged over salinity levels ± standard errors of the means.

4.3.4 Mortality

Salinity increased rice seedling mortality very soon after planting (Figure 4.5). A linear increase in the percentage of dying plants was observed in all three cultivars up to 22 DAT; Amber33 (r^2=0.92), IR45427 (r^2=0.90) and Koshihikari (r^2=0.87). After 22 DAT mortality remained stable. Amber33 and IR45427 cultivars exhibited less mortality (37%) in plants in comparison with Koshihikari (60%), 28 DAT. In the absence of salinity, no rice plants died.

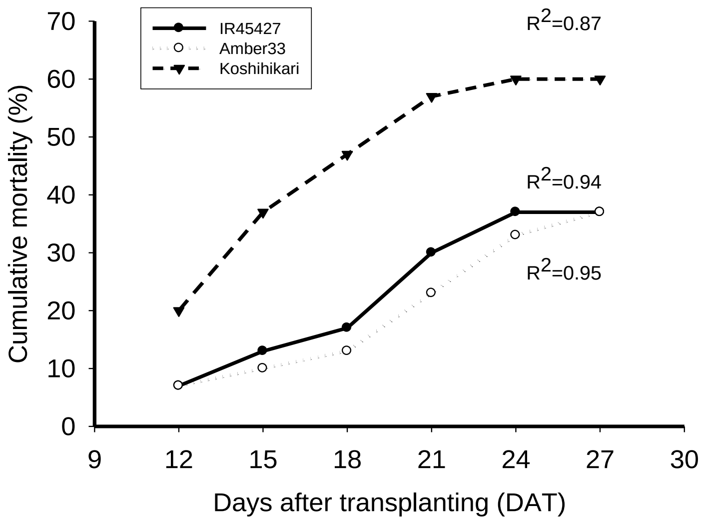
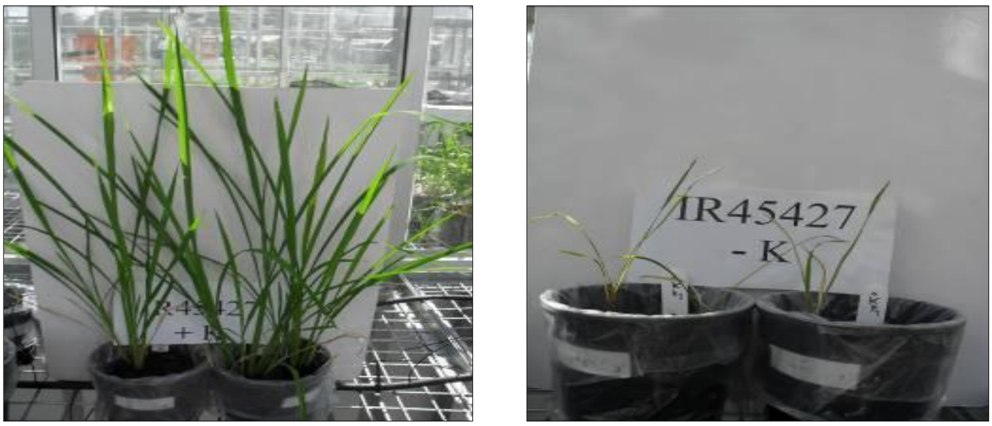


Figure 4.5 Effect of salinity on seedling growth of three rice (*Oryza sativa*) cultivars grown in Vertosol with low available K. Mortality increased linearly up to Day 22 and the linear regression correlations are presented on the graph for each cultivar.

4.3.5 Salinity symptoms on rice

Compared with rice plants grown in the absence of salinity, increased salinity resulted in leaf chlorosis, wilting and finally death (Figure 4.6).



Non-saline soil Saline soil

Figure 4.6 Effect of soil salinity at ~3 dS/m on rice (*Oryza sativa* cv IR45427) grown for 40 days in a glasshouse

4.4 Discussion

4.4.1 Soil solution EC and pH

Electrical conductivity (EC) is a useful measure of soil salinity. Under submerged conditions, an increase in EC occurs following release of exchangeable cations and anions to soil solution (Sahrawat and Narteh 2002). In this study, EC was elevated to near 3 ds/m in the surface soil solution, approximately half the targeted EC range from the preliminary trial (Table 4.1). However, soil submergence often results in surface water leaching of salts which would result in most likely higher salt loads deeper in the pots (Abbas *et al*. 2006; Mehdi *et al*. 2003). As soil solution was sampled from near the surface of flooded pots, it is not unexpected that salinity in the zone of sampling was lower than expected. Surface pH also tended towards neutrality as submergence progressed (Table 4.1). The observed increase in soil pH to near neutral under submerged conditions has been reported by Ponnamperuma (1972). Following flooding, the pH of acid soils (except those low in iron) and alkaline soils converge to a fairly stable value between 6.7 – 7.2. Recent observation of this phenomenon in the field was provided by Mehdi *et al*. (2003). The slow increase in soil pH is not unexpected as the soil used is low in labile C and hence the changes in redox potential that are fundamental to shifts in soil pH following submergence were slow to proceed. Indeed, the method of soil solution extraction may have artificially increased measured soil pH due to degassing of carbon dioxide following extraction of soil solution under vacuum. It is likely that the majority of damage done to rice seedlings under flooded saline conditions is not due to excessively lowered soil pH values and is entirely due to the salt composition of the soil solution.

4.4.2 Soil solution cation composition

Application of salt and cations to soil displaces existing cations from the exchange surface resulting in considerably higher solution cation concentrations (Table 4.2). Over time, prolonged surface application of water to maintain submerged conditions in the pots resulted in leaching of cations below the zone where they were being extracted. These decreases in cation concentration in solution were consistent regardless of whether salt was added or not. However, it should be noted that the decrease in solution cation concentrations, particularly in the non-saline soil conditions may be related to plant uptake.

This initial pilot study sought to determine the effect of salinity and method of K application on plant response, although the extent of mortality was not expected. A secondary purpose for the study was to assess the effect of application strategy on solution K concentrations and determine if a split application would maintain higher K activity in solution later in the growing season. Solution cation compositions in the Amber33 treatments indicated that the ratio of Na:K was highest where K was applied in a split manner early in the growing season of the rice plants (Table 4.3). At the surface of the pots, the more critical value of K activity in solution (AR^K) was higher ($P < 0.05$) with an early upfront application. The observed increase in AR^K is not unexpected, as increases in exchangeable K often result in increased solution K activity (Beckett 1964; Cox and Uribe 1992; Ganeshmurthy and Biswas 1984; LeRoux and Sumner 1968). However the second application of K increased the AR^K significantly ($P < 0.05$). This increase placed it at the same initial AR^K as the upfront application, but later in the season, and with only 60% of the total K applied. Consideration of the solution cation concentrations reveals considerable displacement and loss of Ca and Mg from upper pot solution of split application saline treatments, resulting in a higher observed AR^K. This change in divalent cation composition in solution in this particular treatment is difficult to account for, as divalent cations are generally preferred on the exchange, less likely to be displaced following application of a monovalent cations (relative to Na^+) and should have remained well buffered near the surface of the pots (Tchouaffe 2007).

Regardless, the improved AR^K following a split application has significant implications for plant growth under saline conditions. Higher AR^K values increase plant available K and plant uptake (Al-Zubaidi *et al.* 2008). Plant demand for K is low when plants are young and transpiring surface area is small. Hence a lower K activity in solution should not adversely affect rice growth early in the season. Increasing AR^K later in the growing season matches plant demand for K more closely, particularly near panicle initiation and grain fill. Increasing K availability in soil solution can also reduce Na^+ entry into rice plants, reducing the harmful effects of salinity on plant cell membranes, growth and other metabolic processes (Zayed *et al.* 2007). Under saline conditions, which may be present regularly in Iraqi rice agriculture (Steering committee report 2012), increasing the activity of K in soil solution, later in the season, may increase the efficiency with which K is used by the rice plant and potentially increase rice yields.

4.4.3 Plant mortality

Rice is particularly sensitive to salt stress during the early seedling stage (Flowers *et al.* 2000; Mass and Hoffman 1977; Shereen *et al*. 2005). A 37 – 60% increase in mortality was also observed by Shereen *et al.* (2005) under field conditions. The higher susceptibility of Koshikari to increased salinity is also reported (Abdelgadir *et al.* 2005).

Mortality increased due to the effects of salinity on plant growth either through increased osmotic potential in the soil solution or specific Na ion toxicity (Sheldon *et al.* 2004). Sodium uptake and redistribution results in foliar Na accumulation, leading to leaf mortality and reduced assimilate production (Munns 2002). Under saline conditions, accumulation of excess Na^+ results in leaf damage that may be alleviated if K uptake is possible and optimum leaf tissue Na:K ratios can be obtained (Titov *et al.* 2009).

4.5 Conclusion

This preliminary experiment confirmed cultivar differences in salt tolerance at an early seedling stage, this suggested that the level of salinity imposed was too high to allow competitive interactions for cation uptake at the root surface to be observed due to high seedling mortality and confirmed that a split application of K is likely to result in better solution AR^K and hence plant K uptake later in the growing season. Hence, a second experiment was conducted in the glasshouse at lower salinity (3 – 4 dS/m) to investigate the role of K in K uptake, K^+: Na^+ ratio and yield components using the same three cultivars, Koshihikari, Amber33 and IR45427.

4.6 The effect of K on K uptake and rice yields under saline conditions

Applied salinity levels to achieve 6 – 8 dS/m in soil, constrained rice growth in the absence of K and presence of high N and P (Section 4.5). In general, young seedlings are sensitive to salt stress. Severe injury to seedlings is caused by a high concentration of salts. Three cultivars (IR45427, Amber33 and Koshihikari) with varying susceptibility to salinity were used for comparison. Koshihikari was more susceptible to high salinity compared to IR45427 and Amber33 in the previous study (Section 4.3.4). Overall, 37 – 60 % of plants died within 28 days in the control treatment; also, as the plants that survived were very weak, it was difficult to compare them with the plants from K fertilised treatments. Hence, an experiment was undertaken in the glasshouse to investigate the effect of K fertilisation on plant height, tiller number and the dry weights of shoot and root, at the maximum tillering stage of rice grown under less saline (3 – 4 dS/m) conditions.

4.7 Material and Methods

4.7.1 Soil and rice seeds

A pot experiment was conducted in a glasshouse during the growing season in 2010 at the University of New England (UNE). The soil used in the experiment was the same soil (Vertosol) used in previous experiments (Table 3.1). Rice seeds used in this experiment were supplied by the Yanco Agricultural Institute, Australia and Rice Research Station, Iraq. Seeds germinated on August 16, 2010. Similar sized seedlings were transplanted into lined 150 mm plastic pots of 150 mm deep, after one week. Rice pots were flooded at 20 DAT to a depth of 3 to 5 cm of standing water and remained flooded during the crop growth period. Watering ceased one week before the harvest.

4.7.2 Fertiliser applications

Potassium, as muriate of potash (MOP), (50% K) was applied at 0 or 200 mg K/kg. The 200 mg/kg was applied in two equal applications of 100 mg/kg as upfront dose and 100 mg/kg 30 DAT, with saline (3 – 4 dS/m) Vertosol. Nitrogen as urea, (46% N) was applied in four split doses (50 mg/kg soil, every two weeks). In addition, P fertiliser was applied to all the pots once as upfront dose at a rate of 50 mg/kg soil as calcium tetra hydrogen di-orthophosphate $Ca(H_2PO_4)_2$ (24% P). All treatments were fertilised with S, 20 mg/kg soil as gypsum ($CaSO_4.2H_2O$) (15% S).

4.7.3 Measurements of Plant

Plant height (cm) was measured and tillers per plant were counted during the maximum tillering stage, 41 DAE. Rice stems were taken at 41 DAE from each pot. Roots were collected, and then rinsed with tap water to remove soil**.** After oven-drying at 70˚C for 72 hours, harvested material was ground, and then digested in a mixture of $HClO_4$:H_2O_2 (70/30% v/v). After appropriate dilution, the digested material nutritional status was estimated using ICPAES.

4.7.4 Experiment design

A glasshouse experiment was conducted in a completely randomised design (CRD), with the combination of three rice cultivars and two K levels (0 and 200 kg/ha). All treatments were replicated thrice and pots were randomly arranged on benches in the glasshouse.

4.7.5 Statistical analysis

Two-way analysis of variance of the data for each attribute was carried out and the mean values were compared with the least significance difference (LSD) test using R (R Development Core Team 2003). Results were graphed using SigmaPlot, v.7.

4.8 Results

4.8.1 Cation concentration for rice

4.8.1.1 **Potassium and sodium content**

All three cultivars of rice had higher tissue Na^+ concentration under saline conditions in the absence of K compared with the same cultivars where K was applied. Potassium application significantly ($P < 0.001$) decreased the Na^+ concentration in plant shoot and root tissues. All cultivars accumulate lower Na^+ and higher K^+ in the shoot and root under K fertilised conditions (Figure 4.7a – d). Shoot Na concentration decreased an order of magnitude to negligible levels (Figure 4.7), whilst root Na concentrations decreased by a similar amount, but were initially higher (Figure 4.7). The Na^+ concentration was higher in both IR45427 and Koshihikari, while it was lower in Amber33, which reflected that the cultivars have different rates of Na uptake. As expected, there were significant effects of K application and cultivar ($P < 0.001$) on K concentration of the tops. Furthermore, K concentration in root tissues significantly ($P < 0.001$) increased with the application of K, i.e. Amber33 had K concentration in shoot and root ~17% higher than other cultivars.

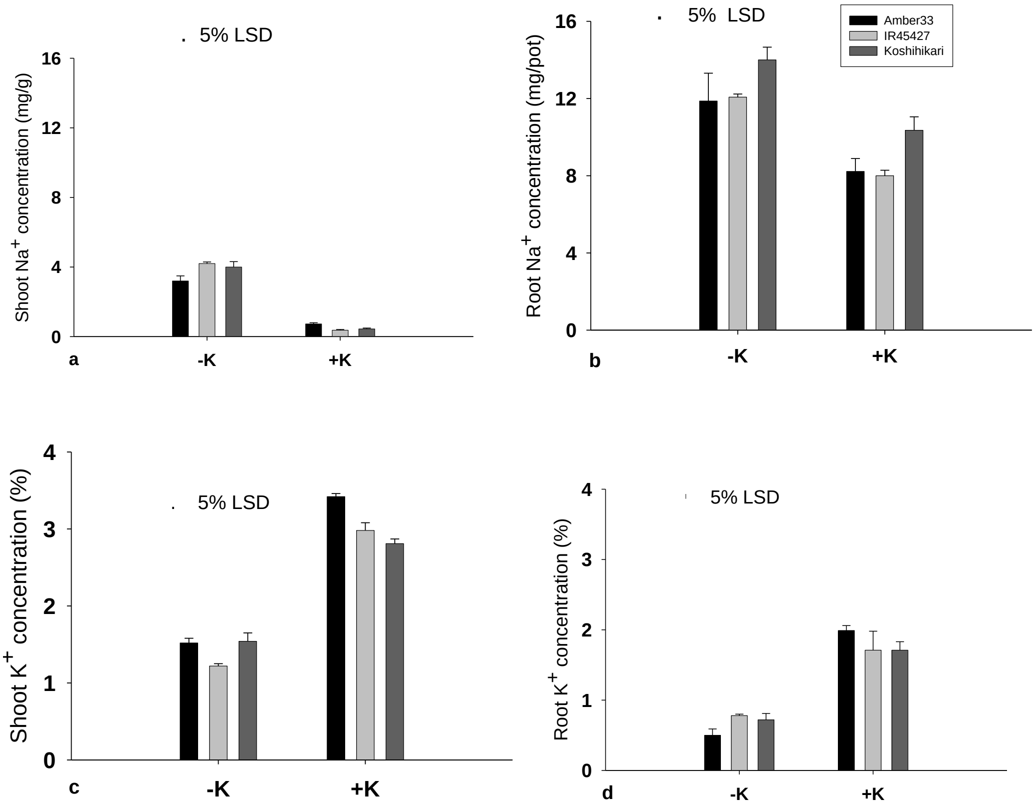


Figure 4.7 Effect of K application (No potassium vs 200 mg K/kg) on Na^+ (a – b) and K^+ (c – d) concentrations in shoots and roots of three rice (*Oryza sativa*) cultivars grown for 41DAE in a glasshouse on a K responsive Black Vertosol. Values are the mean of 3 replicates.

4.8.1.2 **Calcium and magnesium content**

The Ca^{2+} and Mg^{2+} concentrations of shoot tissues for all cultivars were higher at saline conditions (3 – 4 dS/m) in the absence of K. Application of K fertiliser decreased ($P < 0.001$) shoot Ca^{2+} and Mg^{2+} concentrations in all cultivars (Figure 4.8a and c). Koshihikari had significantly lower tissue Ca concentrations regardless of K application ($P < 0.001$) (Figure 4.8). There were no significant trends associated with K application on root tissue Ca^{2+} and Mg^{2+} concentrations (Figure 4.8). Amber33 did however have significantly higher root tissue Mg^{2+} concentrations (Figure 4.8d).

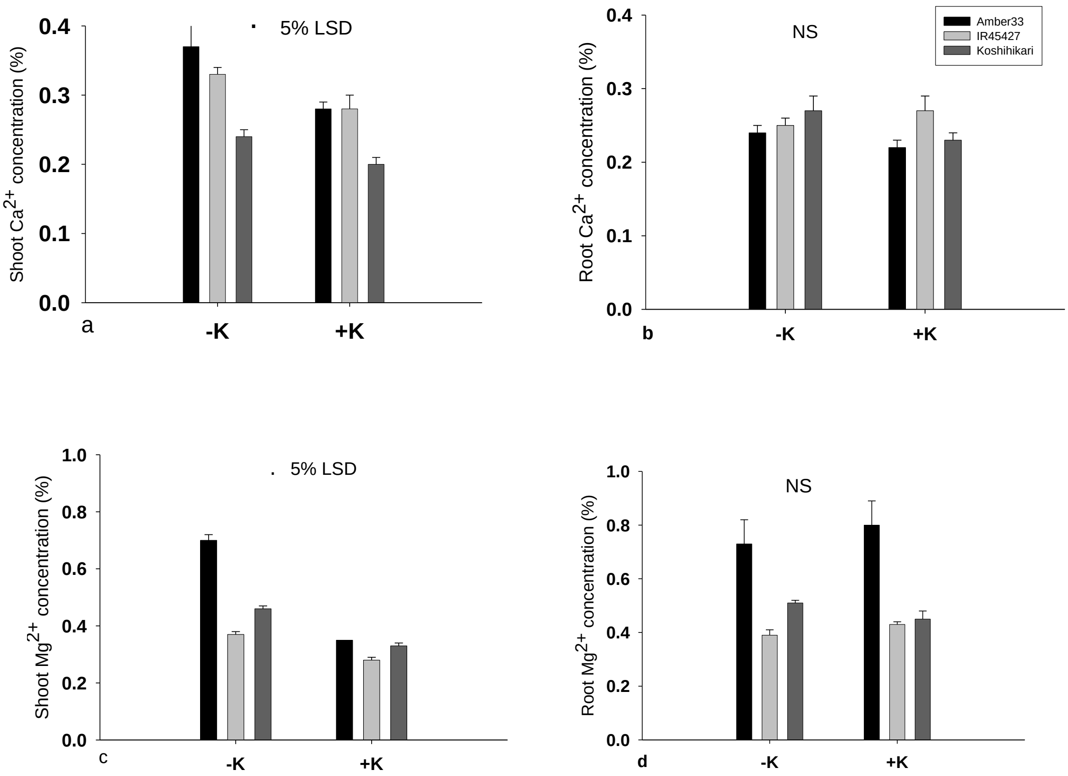


Figure 4.8 Effect of K application (no potassium vs 200 mg K/kg) on Ca2+ (a – b) and Mg2+ (c – d) concentrations in shoots and roots of three rice (*Oryza sativa*) cultivars grown for 41DAE in a glasshouse on a K responsive Black Vertosol. Values are the mean of 3 replicates.

4.8.2 Cation uptake for rice

4.8.2.1 Potassium and sodium uptake

Uptake of Na^+ decreased ($P < 0.001$) with the addition of K (Figure 4.9a). In shoots, the concentrations of Na^+ decreased from 7 to 3, 23 to 2 and 17 to 2 mg/pot of Amber33, IR45427 and Koshihikari, respectively. However, no significant ($P=0.204$) effect of K addition on Na^+ uptake by roots was observed. Amber33 had significantly lower Na and K uptake ($P < 0.001$) (Figure 4.9). As expected, K application significantly ($P < 0.001$) increased the K uptake by plant shoot and root tissues. Potassium uptake by shoot and root increased significantly ($P < 0.001$) among cultivars.

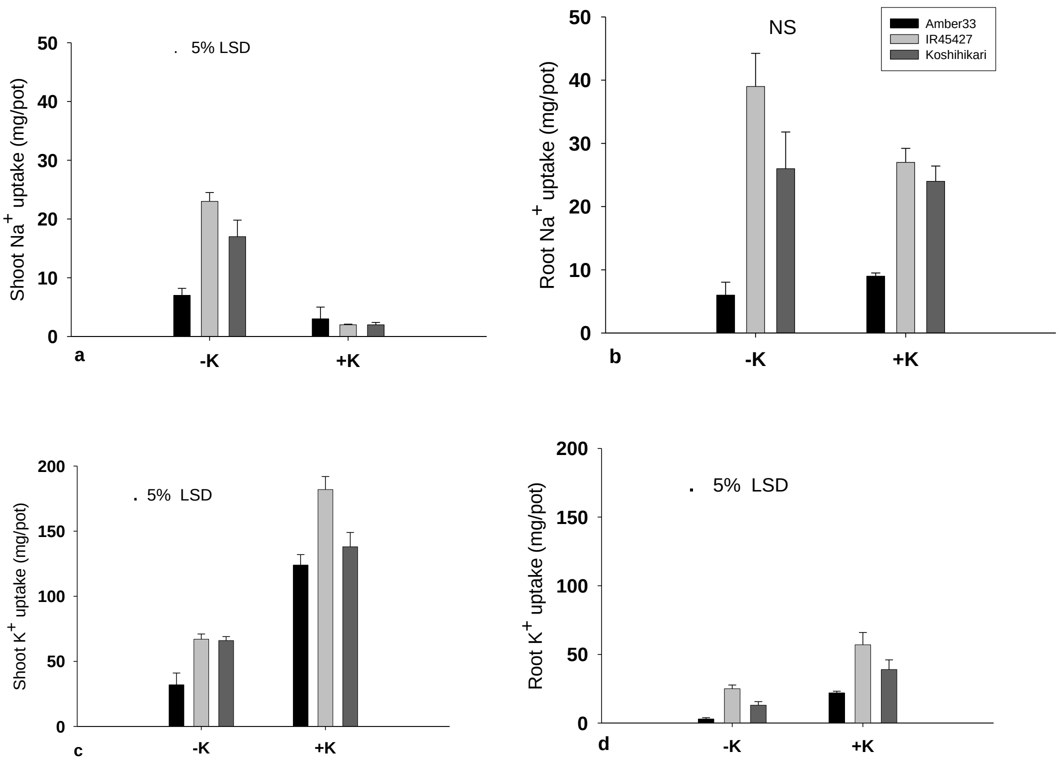


Figure 4.9 Effect of K application (No potassium vs 200 mg K/kg) on Na^+ (a – b) and K^+ (c – d) uptakes by shoots and roots of three rice (*Oryza sativa*) cultivars grown for 41DAE in a glasshouse on a K responsive Black Vertosol. Values are the mean of 3 replicates.

4.8.2.2 **Calcium and magnesium uptake**

Magnesium uptake was not affected (P=0.13) by application of K fertiliser. However, Mg and Ca uptake were significantly (P < 0.001) higher in IR45427 (short cultivar) than the taller cultivars. The effect of K addition on Ca^{2+} uptake was not significant (Figure 4.10).

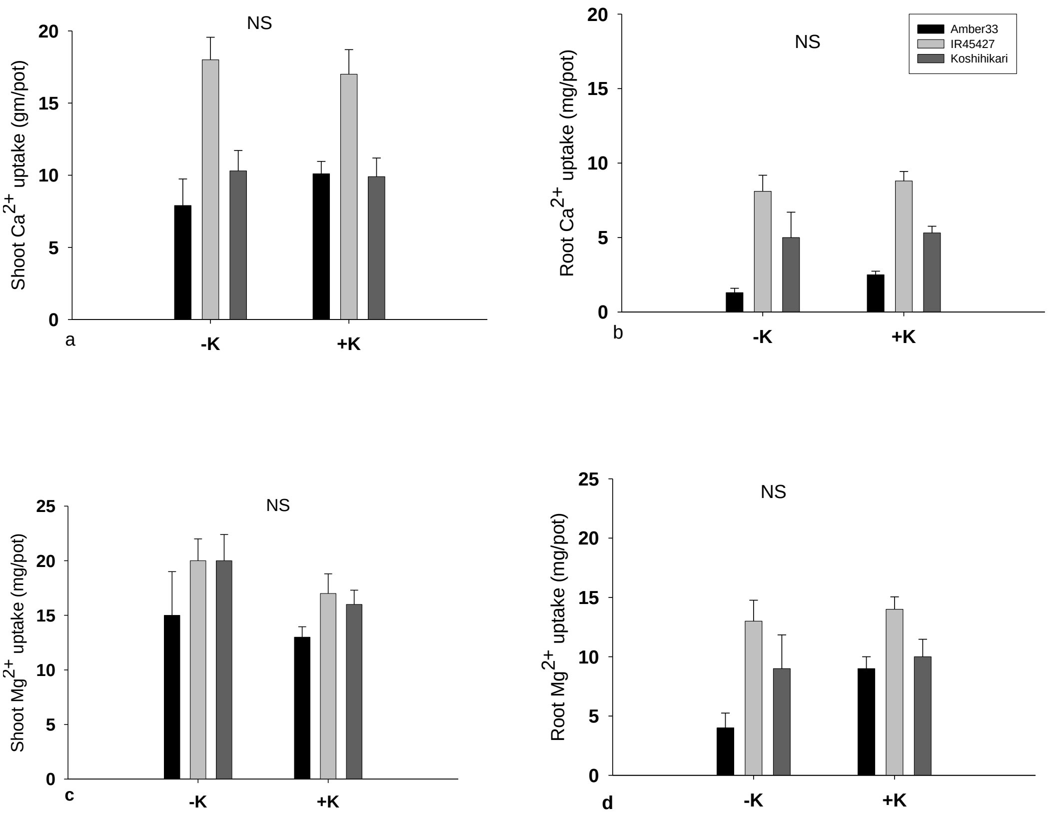


Figure 4.10 Effect of K application (no potassium vs 200 mg K/kg) on Ca^{2+} (a – b) and Mg^{2+} (c – d) uptakes by shoots and roots of three rice (*Oryza sativa*) cultivars grown for 41DAE in a glasshouse on a K responsive Black Vertosol. Values are the mean of 3 replicates.

4.8.3 Plant height

All three cultivars responded to extra K under saline conditions (Figure 4.11). Koshihikari was taller ($P < 0.01$) than Amber33 and IR45427. Potassium application increased the plant height of IR45427, Amber33 and Koshihikari by 10, 21 and 12% respectively, but there was no interaction between K and cultivar.

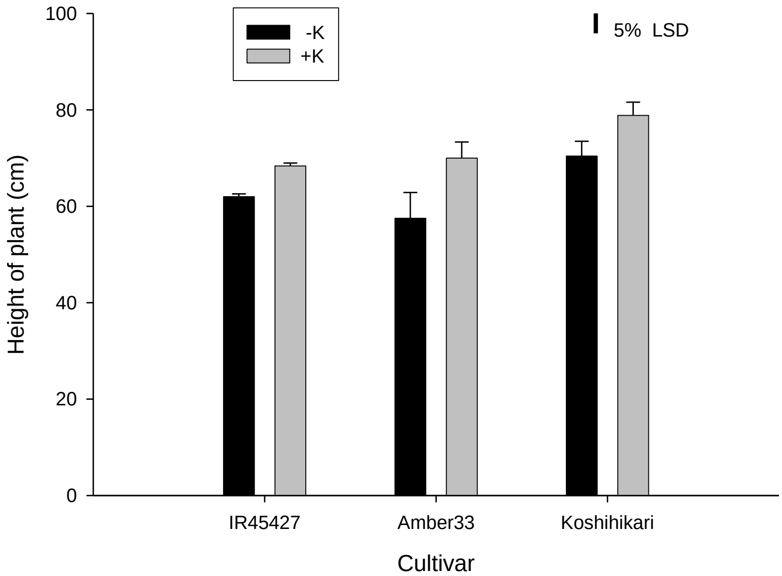


Figure 4.11 Effect of K application (no potassium vs 200 mg K/kg) on plant height (cm) of three rice (*Oryza sativa*) cultivars grown for 41DAE under salinity conditions in a glasshouse on a K responsive Black Vertosol. Values are the mean of 3replicates with ± standard error indicated by bars.

4.8.4 Tiller number

Potassium again increased tiller production in this experiment (Figure 4.12). Potassium increased ($P < 0.01$) tiller numbers by 23, 69 and 35% for IR45427, Amber33 and Koshihikari respectively.

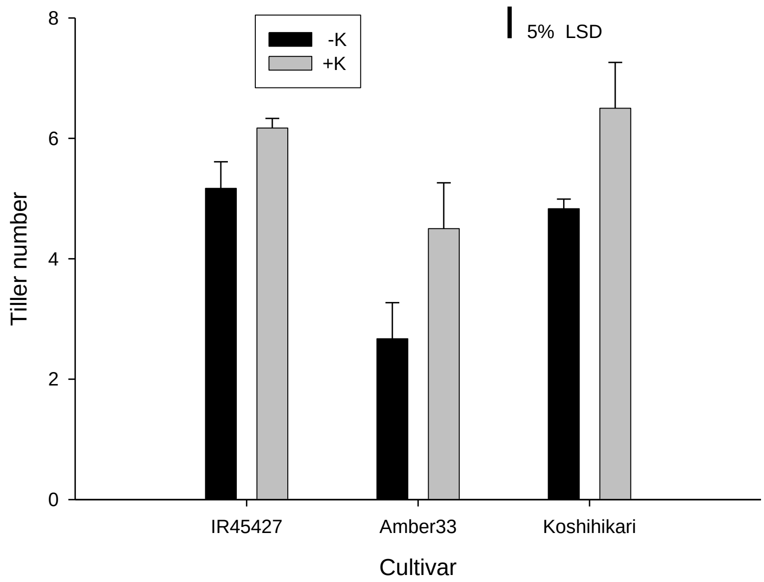


Figure 4.12 Effect of K application (No potassium vs 200 mg K/kg) on tillering of three rice (*Oryza sativa*) cultivars grown for 41DAE under salinity conditions in a glasshouse on a K responsive Black Vertosol. Values are the mean of 3 replicates with ± standard error indicated by bars.

4.8.5 Shoot and root dry weight

Shoot dry weights (SDW) and root dry weights (RDW) of the three rice cultivars significantly ($P < 0.05$) increased with K addition (Figure 4.13). Though the response of cultivars differed significantly ($P < 0.001$) with added K, shoot dry weight increased by 12, 70 and 14% in IR45427, Amber33 and Koshihikari, respectively. There was no interaction between K and cultivar.

A similar trend was also observed in RDW of these cultivars (Figure 4.14). Potassium application significantly ($P < 0.05$) increased RDW production by 3, 109 and 23% in IR45427, Amber33 and Koshihikari, respectively.

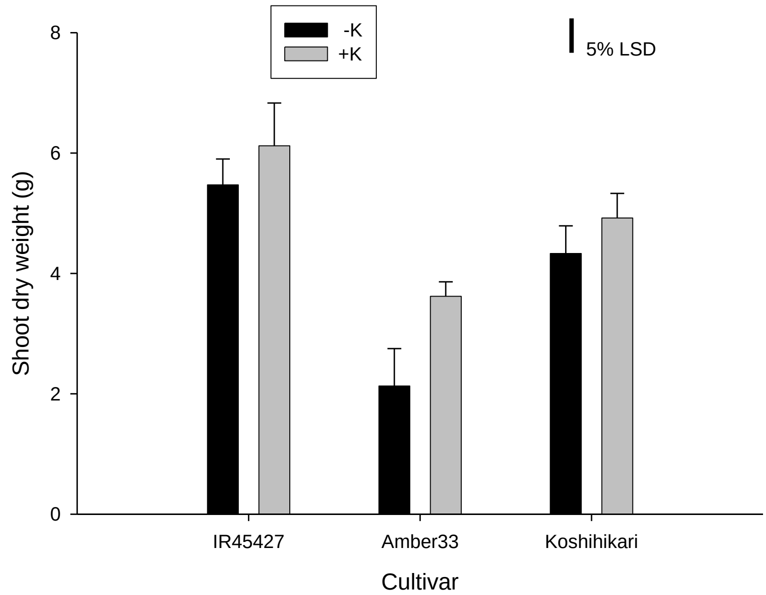


Figure 4.13 Effect of K application (No potassium vs 200 mg K/kg) on SDW (g) of three rice (*Oryza sativa*) cultivars grown for 41DAE under salinity conditions in a glasshouse on a K responsive Black Vertosol. Values are the mean of 3replicates with ± standard error indicated by bars.

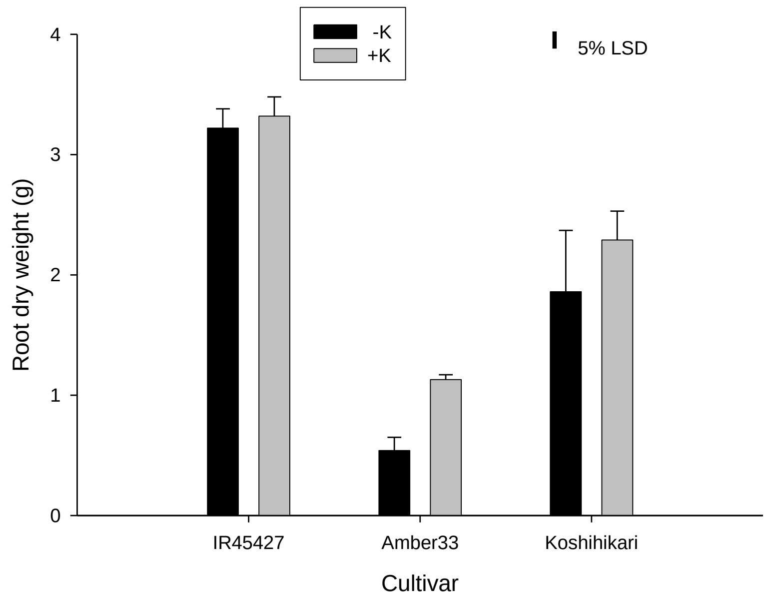


Figure 4.14 Effect of K application (no potassium vs 200 mg K/kg) on RDW (g) of three rice (*Oryza sativa*) cultivars grown for 41DAE under salinity conditions in a glasshouse on a K responsive Black Vertosol. Values are the mean of 3 replicates with ± standard error indicated by bars.

4.9 Discussion

Under saline conditions, Na uptake in rice varies with cultivar. Amber33 demonstrated the lowest Na uptake, however this was driven almost entirely by the low dry matter accumulation relative to the two other cultivars. Application of K also significantly reduced Na uptake in all cultivars, to negligible levels, predominantly through reduced tissue Na concentrations. The results of this study demonstrate conclusively that K fertilisation of rice under saline, Na dominated solution concentrations, has the potential to overcome some of the constraints associated with salinity damage. The mechanism for this improvement is likely to be cation competition at the root cell membrane, inhibiting Na uptake into the plant.

Other researchers have also demonstrated that competition for monovalent cation uptake at the root membrane is affected by the relative availability, in fact activity, of Na and K in the soil solution. In the presence of high Na, increased Na uptake is commonly observed (Kamboh *et al*. 1999; Momayezi *et al*. 2010). Within the plant however, improved K nutrition also helps alleviate Na induced osmotic stress (Munns *et al.* 2002) and intracellular tolerance of excess Na is increased in the presence of K (Endris and Mohammed 2007; Zayed *et al.* 2007).

Excess amount of soluble salts in root medium is an important constraint to rice production in soils of semi-arid and arid regions where Iraq is located. The result showed that external application of K ameliorated the adverse effects of salt stress. Increased K uptake and decreased Na uptake by addition of K in this study was the main mechanism responsible for better growth of rice. Under saline conditions, K application significantly increased height of plant, tiller number, shoot and root dry weights (Figures 4.11, 4.12, 4.13 and 4.14) and this could eventually lead to a significant increase in rice production.

There was a significant decrease in Ca^{2+} content in plant tissues with increasing K^{+} concentration in the solution (except the root Ca^{2+} concentration in IR45427 cultivar) as the higher external K^{+} content competed with Ca^{2+} ions for uptake (Fageria 1983; Munns *et al.* 2002).

Evidence from previous work (Wu *et al*. 2009) indicates that most plants tend to take up Na^{+} ions under limited supply of K to compensate for cation balance. By ensuring adequate supply of K, therefore, the harmful effects of Na^{+} can be avoided by suppressing its uptake through adequate supply of K.

Increasing K dosage helped the rice plants to grow faster during vegetative stage, due to the fact that K encourages cell division and elongation, resulting in taller plants and increased tillering. Potassium produces more shoot and root dry matter with less catabolism due to the salinity stress. This improved growth may be related to improved cell turgor, enzymatic activity and reduced Na uptake (Zayed *et al.* 2007).

Under salt stress, K^{+} is mostly replaced by Na^{+}, which affects the turgor function of vacuolar K^{+}. The inhibitory effect of Na^{+} on K^{+} uptake mechanisms can create K^{+} deficiency (Munns 2002). The build-up of cytoplasmic Na^{+} can obstruct the catalytic role that K^{+} plays in many metabolic processes (Maathuis 2006). These conditions can also limit the role of K in cell division in the shoot and root and in controlling the length and radius of the roots, overall root growth and the root hair density (Havlin *et al.* 2005; Kumar 2009; Surendran 2005).

High external Na^+ concentrations may cause K^+ seepage out of the cell, ultimately leading to reduction in cell growth (Kant and Kafkafi 2002). Furthermore, salt stress might result in limited transport of essential nutrients such as K^+, Ca^{2+}, Mg^{2+} and total N, to the shoot of plants (Termaat and Muuns 1986).

It can be concluded that, salinity affected the growth and increased mortality of rice plants. However, K application resulted in better crop growth, as evident from increased height, tiller numbers and plant biomass. Potassium fertiliser partially mitigated the adverse effect of salinity under conditions that could be considered representative of those found in Iraq. However, further research is necessary to confirm the observed mechanisms occur under field conditions and under a range of salinity and K application rates. So, when rice is cultivated in saline environment, K application might be one of the factors to be considered for improving the crop production. These results confirm the findings from our previous study (Sections 3.3.2 and 3.4.1) that these parameters are affected by K application.

4.10 Conclusion

This study demonstrated that rice growth can be enhanced by K fertiliser addition under saline conditions. Increasing K availability in the soil solution effectively reduces Na^+ influx into rice plant. Soil solution studies described earlier in the chapter demonstrate that K activity in solution is maintained at a higher level, later in the growing season through split application of K, lengthening the effective period over which Na influx could potentially be alleviated. However, early application of the split dose is preferable to late application as soil salinity decreases in the root zone over the growing period associated with a slow leaching of salts in the coarser textured, low CEC soils common to Iraq (Chapter 6). Additional work is needed to verify these findings under field conditions.

The question now is, whether K application is needed for Iraqi soils? Although the studies by Al-Zubaidi and Pagel (1979) and Edan *et al.* (1987) have shown that Iraqi soils are rich in exchangeable K, these soils have high capacity of K fixation due to the presence of beidillite mineral (Na.Ca0.5)0.3Al 2(Si.Al) $4O_{10}(OH)_2$. nH_2O (smectite family). Hence, the release of K is very slow from these soils. Our study suggests that Iraqi soils, with low available K, will respond to K addition, and K fertilisation can increase rice production in Iraq.

CHAPTER 5: **POTASSIUM AND RICE ROOT GROWTH**

5.1 Introduction

The plant root system captures water and nutrients from the soil and provides plant anchorage against uprooting forces. Root growth response to K was measured in a glasshouse experiment with two rice cultivars (IR45427 and Amber33). Earlier studies (Chapter 3) suggested that lodging of rice under high N and P fertility was associated with basal lodging, and that K nutrition increased RDW proportionally more than SDW. This study aimed to examine in more detail the effect of K on root parameters such as root length, surface area, root volume and root diameter under different rates of K and the implications of changed root parameters on anchorage of rice roots. In addition, this study sought to examine whether application of K changed the pattern of root response in favour of surface rooting that may provide better basal anchorage against lodging.

5.2 Method

5.2.1 Soil

A non-sodic non-saline Vertosol of low K status (~0.2 $cmol_c$/kg) was used in this trial. Soil was collected from a depth of 10 – 20 cm from northwest of Armidale on 6th October 2010. The soil was air dried for two weeks and aggregates were crushed through a grinding machine to less than 1 cm. The homogenized soils were then put in lined plastic columns of 15 cm top diameter × 100 cm deep. The main characteristics of the soil used were presented in Table 3.1.

5.2.2 Experiment design

The study was conducted during the 2010 – 2011 growing season. The experiment used completely randomised design (CRD) of two factors (K and cultivar). There were three rates of K (0, 100 and 200 mg/kg) and two cultivars with eight replicates.

5.2.3 Seeds source and germination

Rice seeds of Amber33 and IR45427 were supplied by Rice Research Station in Iraq and the Yanco Agricultural Institute, Australia, respectively. Seeds from each cultivar were germinated on 20th October 2010 at day/night temperatures of 30/25˚C with a light intensity of ~800-Lux, on moist filters paper in a plant growth cabinet (germinator) without nutrients and they were watered with de-ionised water only. Seedlings of similar size were then transferred after one week into soil in plastic columns. Each column contained 17.5 kg soil with one rice plant. The average mean temperature during the entire growing season was 30 /25˚C day/night. Plants were grown to final grain harvest. All root parameters were determined at final harvest on 28th February 2011 (Figure 5.1).

15 DAT 95 DAT

Figure 5.1 Glasshouse experiment, located at UNE, Armidale, 2010–2011

5.2.4 Fertiliser management

Each soil column was supplied with 200 mg N/kg soil as urea (CO $(NH_2)_2$) (46% N) in four-split applications at a rate of 50 mg/kg soil every fortnight. Potassium was added to the soils as potassium sulphate K_2SO_4 (45% K) at the rates of (0, 100 and 200 mg/kg soil) with half at planting through the soil volume and half as a surface application 30 days after transplanting (DAT). Nitrogen was applied. In addition, phosphorus (P) fertiliser was applied to all pots once at planting at a rate of 50 mg/kg soil as calcium tetra hydrogen di-orthophosphate $Ca(H_2PO_4)_2$ (24% P). Sulphur (S) was applied at 82 mg S/kg as gypsum $CaSO_4{\cdot}2H_2O$ (15% S) as a basal dose to the treatments without K and at 41 mg S/kg to the treatments with 100 mg K/kg, hence all pots received the same amount of S. Fertilisers were mixed uniformly with the surface 2 kg of the soil columns.

5.2.5 Water management

The columns (15 × 100 cm) were watered with rain water using an automatic watering system three times daily for the whole growing period, which was 100 days for IR45427 and 150 days for Amber33, to maintain the plants under flooded conditions with 3 – 4 cm of standing water above the soil surface.

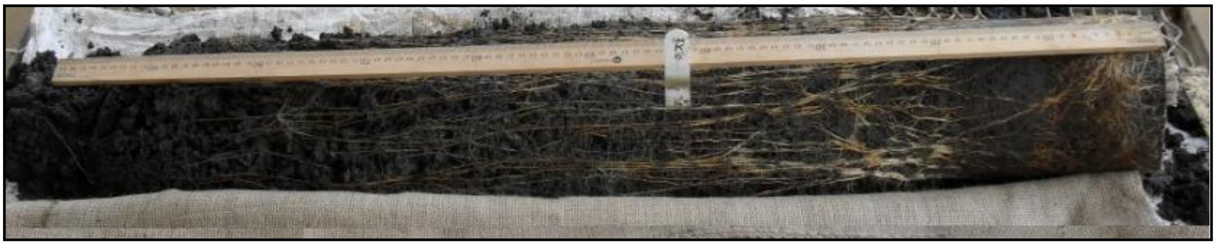
5.2.6 Root system measurements

Watering was stopped for 20 days prior to harvest to allow the soil core to be removed easily from the pots (Figure 5.2a – b). The soil core was divided into seven depths (0 – 5, 5 – 10, 10 – 15, 15 – 30, 30 – 45, 45 – 60 and 60 – 90 cm). To recover the roots, each depth section of soil was placed in 0.2% (w/v) of Na (PO_3) n. Na_2O (Calgon) solution. After soaking for two hours, roots were collected, washed through a 1-mm mesh screen to separate the roots from the soil in tap water then preserved in 1:1 water- alcohol mixture and stored in a cool room. Roots were then gently rinsed for 3 minutes, cut into length of 1 – 1.5 cm length, and then placed in 0.05% toluidine blue stain for 3 minutes. The stained roots were gently rinsed under running water for 3 minutes and then carefully spread into a thin layer of deionised water (2 – 3 mm) in a transparent 300 cm^2 tray. The root samples were scanned at a resolution of 400 dots per inch (dpi), by the *Win- Rhizo* images analysis system (Regent Instruments Company, Canada), coupled with a professional scanner Epson Perfection V 700 photo. Then the root characteristics were determined as follows: total root length (RL) (cm), root surface area (SA) (cm^2), and root diameter (mm). Finally, roots were dried in an oven at 50 ˚C for 72 hours to calculate the dry weight in each depth.

Root length density (RLD) (cm of root/cm^3 of soil) was calculated from the total length of roots sampled. Root mass density (RMD) (g of root/cm^3 of soil) was calculated from the total weight of roots sampled. Root distribution was calculated as a percentage of the total root length in each soil depth.

The root to shoot (R:S) ratio was calculated by dividing the total weight of roots by that of shoots. Root biomass (%) was calculated from the dry weight of roots in each soil depth divided by total weight of the roots.

a



b

Figure 5.2 Effect of K application at rate of 100 kg/ha on roots system of two rice (*Oryza sativa*) cultivars IR45427 (a) and Amber33 (b) grown for 100 and 150 DAT, respectively in a glasshouse on a K responsive Black Vertosol.

5.2.7 Statistical analysis

Results were analysed using two-way analysis of variance (ANOVA) using R statistical package (R Development Core Team 2009). Eight replications were used for agronomic traits, but only three replications were used for *win-Rhizo* analysis system as preliminary investigation suggested that the variance was very small. Results were graphed using SigmaPlot, v.7.

5.3 Results

5.3.1 Agronomic characters of rice shoots

Amber33 was 46% taller ($P < 0.01$) than IR45427 at final harvest. Potassium did not significantly increase plant height in either cultivar at 100 kg K/ha ($P > 0.01$), but increased height by 7% in both cultivars at 200 kg K/ha ($P < 0.01$) (Figure 5.3a). Potassium application also significantly ($P < 0.05$) increased the number of productive tillers in both cultivars; however the increase in tiller number was 8% larger in IR45427 compared with Amber33 at final harvest (Figure 5.3b).

Similarly, at final harvest panicle length (PL) significantly ($P < 0.05$) increased by 3.2% following 100 mg K/kg and a further 6.5% at 200 mg K/kg in IR45427. However PL in Amber33 did not significantly increase ($P > 0.05$) (Figure 5.3c). Figure 5.3d shows that the interaction effect between K and cultivar significantly ($p < 0.001$) increased shoot dry matter production by 9 – 22% at final harvest.

Grain yield (GY) per plant was significantly ($P < 0.01$) affected by K application when 100 kg K/ha was applied (Figure 5.3e). It increased by 12 – 22%; however the increase in grain yield was greater in Amber33 than IR45427.

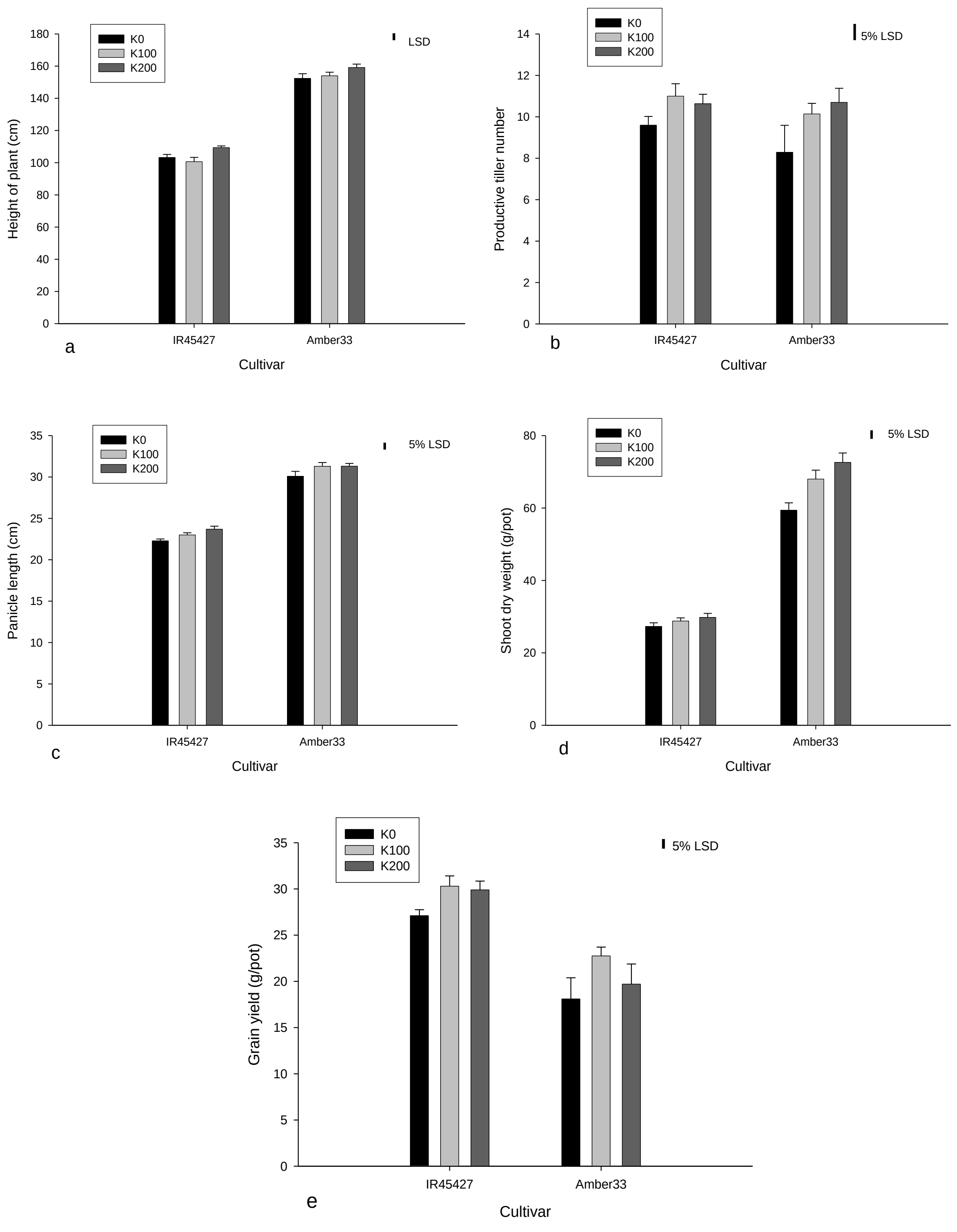


Figure 5.3 Effect of K application on plant height (a), tillering (b), panicle length (c), shoot dry weight and grain yield (e) of two rice (*Oryza sativa*) cultivars IR45427 and Amber33 grown in a glasshouse on a K responsive Black Vertosol. Values are the mean of 8 replicates with ± standard error indicated by bars. Only shoot dry weight possessed significant interaction between cultivar and K rate.

5.3.2 Root morphological parameters

5.3.2.1 **Fresh weight root production**

Significant (P < 0.001) differences between cultivars were found for root fresh weight (RFW) with K application (Table 5.1). Potassium increased RFW of all depths in both cultivars, but at some depths, 100 kg K/ha resulted in higher RFW than 200 kg K/ha. The two cultivars showed major differences in RFW production; in the 15 – 30 cm depth, Amber33 produced 10 times the RFW of IR45427. However, in Amber33 there was a relatively small response to K application. For IR45427, the total RFW increased by 82 and 73% at K levels 100 and 200 kg/ha, respectively, when compared to the control treatment. Similarly, in Amber33 at the same K levels, the RFW was approximately 49 and 61% greater than the control.

Table 5.1 Effects of K application at rates of 0, 100 and 200 kg/ha on root fresh weight (g) of two rice (*Oryza sativa*) cultivars grown in a glasshouse on a K responsive Black Vertosol. Values are the mean of 3 replicates with ± standard errors of the means.

Depth (cm)	IR45427 Root fresh weight (g)			Amber33 Root fresh weight (g)		
	K0	K100	K200	K0	K100	K200
0-5	13.9±0.95	24.7±2.86	21.4±1.42	30.4±1.17	46.8±2.7	48.2±3.97
5-10	2.8±0.41	4.8±0.52	5±0.88	7.8±0.7	11.2±0.43	11.3±0.85
10-15	2.9±0.59	3.38±0.42	4.02±0.57	5.3±0.35	6.6±0.51	9.05±0.37
15-30	0.84±0.27	3.02±0.44	2.24±0.33	8.7±0.32	9.7±0.26	12.07±0.75
30-45	0.52±0.3	1.42±0.45	2.42±0.95	4.4±0.31	7.32±0.27	8.4±0.69
45-60	0.13±0.03	0.69±0.19	0.76±0.19	3±0.20	5.26±0.19	5.2±0.46
60-90	0.05±0.02	0.47±0.07	0.65±0.17	0.57±0.09	2.99±0.53	2.9±0.17
LSD (0.05)	**0.44**					
Total weight	21.14	38.48	36.49	60.17	89.87	97.12

Root biomass

In both cultivars, there were noticeable differences (P < 0.001) at final harvest in the distribution of root biomass (RB) with soil depth following K application (Table 5.2). In IR45427 and Amber33, 68.6% and 58.5% of total roots (TR) respectively were present in the top 5 cm of soil in the control treatment, while 71% and 62% of roots in IR45427 and Amber33, respectively were present at this depth when 100 kg K/ha was applied. With K application, the total RB was well developed down to the 60 – 90 cm depth with an increase of 400% in IR45427 and 155% in Amber33 in total RB compared to the control at this depth.

Table 5.2 Effect of K application at rates of 0, 100 and 200 kg/ha on the percentage of roots in different soil depths of two rice (*Oryza sativa*) cultivars grown on a K responsive Black Vertosol. Values are the mean of 3 replicates with ± standard errors of the means.

Soil depth (cm)	IR45427 Distribution root biomass (%)			Amber33 Distribution root biomass (%)		
	K0	K100	K200	K0	K100	K200
0-5	68.6±5	71±1.1	66±2.4	58.5±1.9	62±0.84	61.1±2.8
5-10	13.8±1.7	11.2±0.99	13.4±0.92	11.1±0.7	10±0.9	9.5±0.23
10-15	10.7±1.9	7.1±0.27	8.8±1.2	7.8±0.45	6±0.19	6.8±0.77
15-30	4±1.5	5.7±0.38	5.6±0.91	11.6±0.93	9±0.36	9.5±0.49
30-45	2±0.96	2.9±0.4	3.8±0.84	6±0.62	6±0.14	6.7±0.82
45-60	0.47±06	1.6±0.34	1.9±0.49	4.1±0.34	4.1±0.14	4±0.58
60-90	0.19±0.8	0.95±0.08	0.89±0.19	0.94±0.18	2.4±0.35	2.4±0.33
LSD (0.05)	**0.17**					

Root/Shoot ratio

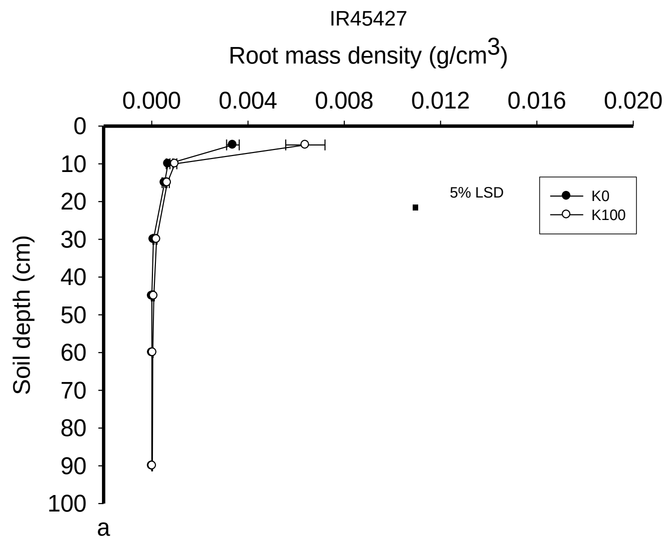
At final harvest, root/shoot ratio (RSR) significantly ($P < 0.001$) increased by 44% following 200 kg K/ha and 75% at 100 kg K/ha for IR45427 (Table 5.3). However, in Amber33, an increase in RSR of 26% following 100 kg K/ha and 30% at 200 kg K/ha was observed.

Table 5.3 Effect of K application on root/shoot dry weight ratios of two rice (*Oryza sativa*) cultivars grown in a glasshouse on a K responsive Black Vertosol. Values are the mean of 8 replicates with ± standard errors of the means.

IR45427				Amber33		
Treatment	Root (g)	Shoot (g)	Root/Shoot	Root (g)	Shoot (g)	Root/Shoot
K0	4.39±0.27	27.5±1.4	0.16±0.008	13.55±0.45	60.15±2.78	0.23±0.013
K100	7.94±0.95	29.08±1.35	0.28±02	19.3±0.94	67.31±1.83	0.29±0.014
K200	7.01±0.51	30.19±1.72	0.23±0.007	22.3±2.94	72.64±3.64	0.30±0.09
LSD (0.05)	**0.03**					

Root mass density

Potassium significantly increased ($P < 0.001$) root mass density by 74 and 100% for IR45427 and Amber33, respectively following K application, and the root mass density of Amber33 was 150% larger than IR45427 at 0 – 15 cm depth (Figure 5.4). At 90 cm depth, root mass density was 775% for IR45427 and 229% for Amber33 over the control.



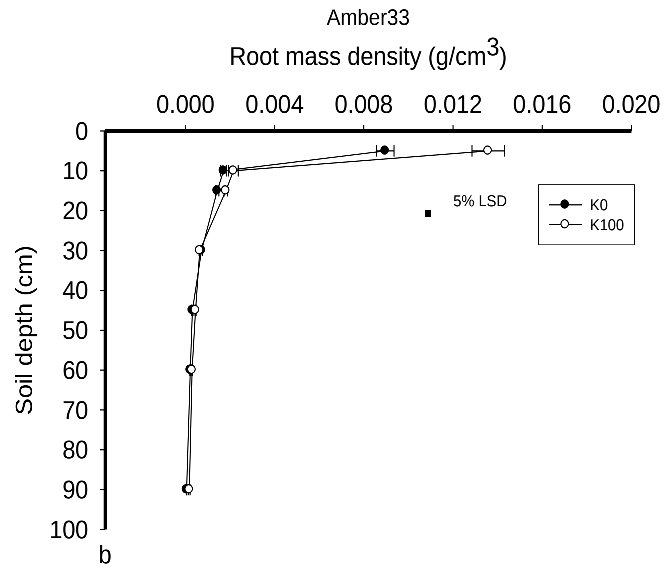


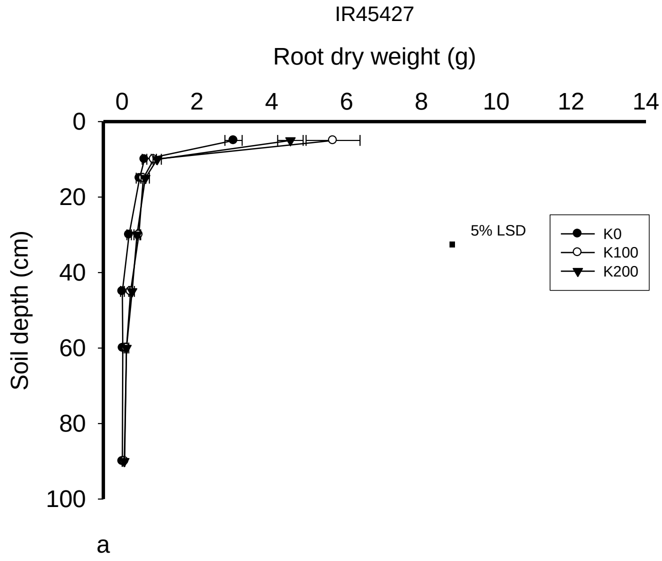
Figure 5.4 Effect of K application at 100kg/ha on root mass density (g root/cm^{3}soil) in two rice (*Oryza sativa*) cultivars IR45427 (a) and Amber33 (b) grown on a K responsive Black Vertosol. Values are the mean of 3 replicates with ± standard errors indicated by bars.

Rooting depth

Rooting depth (RD) of both cultivars was significantly ($P < 0.001$) influenced by K application by final harvest (Figure 5.5). There was an increase in root dry weight in a subsoil layer (20 – 40 cm) for Amber33 and that response was not observed in IR45427 ($P= 0.06$). IR45427 reached rooting depths of 90 cm in both the control and 100 kg K/ha treatments, respectively. A similar trend was observed in Amber33, it reached a depth of 90 cm in both treatments (no K-addition and 100 kg K/ha), by 150 DAT. Amber33 had much greater amount of root showed in the 10 – 30 cm soil depths than IR45427 with K treatments.

Root distribution

There was significant cultivar-by-K rate interaction for root distribution (RD) (by volume) ($P < 0.01$) with the soil depth (Figures 5.6). In IR45427, RD of 3.5 cm^3 root/cm^3 soil was observed at 0 – 5 cm depth, an increase of 298% and 219% at the depth of 5 and 90 cm, respectively following 100 kg K/ha. A similar trend was observed in Amber33, 2.76 cm^3 /cm^3 at 0 – 5 cm depth, which was 80% larger than that in the control treatment. Also an increase by 254% at 90 cm soil depth in RD of Amber33 was observed.



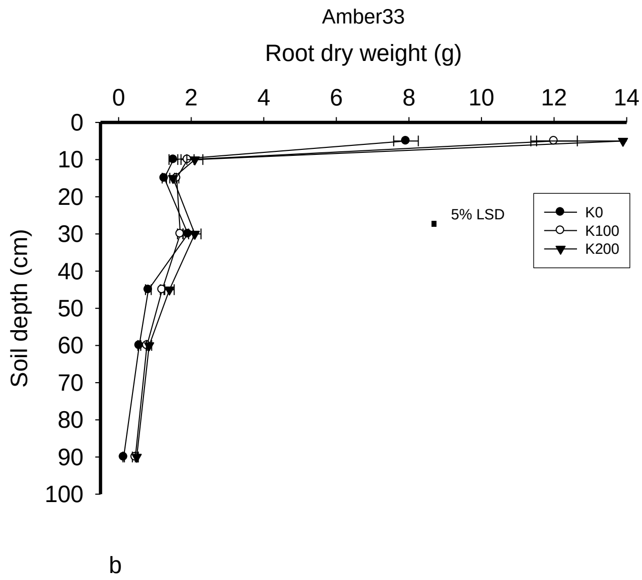


Figure 5.5 Effect of K application on rooting depth of two rice (*Oryza sativa*) cultivars IR45427 (a) and Amber33 (b) grown in a glasshouse on a K responsive Black Vertosol. Values are the mean of 3 replicates indicated by bars.

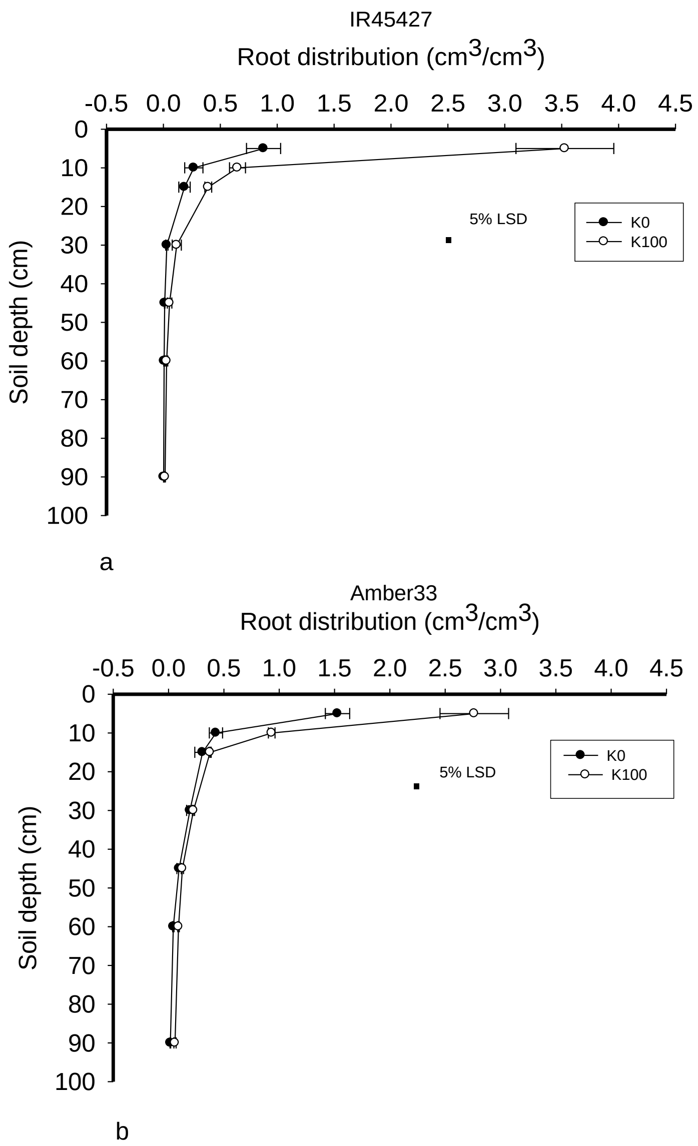


Figure 5.6 Effect of K application on root distribution (cm^3 root/cm^3 soil) of two rice (*Oryza sativa*) cultivars IR45427 (a) and Amber33 (b) grown on a K responsive Black Vertosol. Values are the mean of 3 replicates with ± standard errors indicated by bars.

5.3.2.2 **Root length, root surface area and root volume**

Root length (RL), root surface area (RSA) and root volume (RV) were significantly ($P < 0.05$) affected by cultivar, K rate and soil depth with interactions between these treatments

(Figures 5.7, 5.8 and 5.9). As compared to that in the control treatment, 100kg K/ha provided a large significant ($P < 0.001$) increase of 256% of total root length, 165 % in surface area, and 251% in root volume per plant for IR45427 at final harvest. This level also provided a large significant ($P < 0.001$) increase of 60% in total root length, 56 % in surface area, and 68% in root volume per plant for Amber33, at this stage.

Because there was no significant difference between 100 and 200 kg K/ha treatments, root measurements were carried out on rice plants that received 100 kg K/ha.

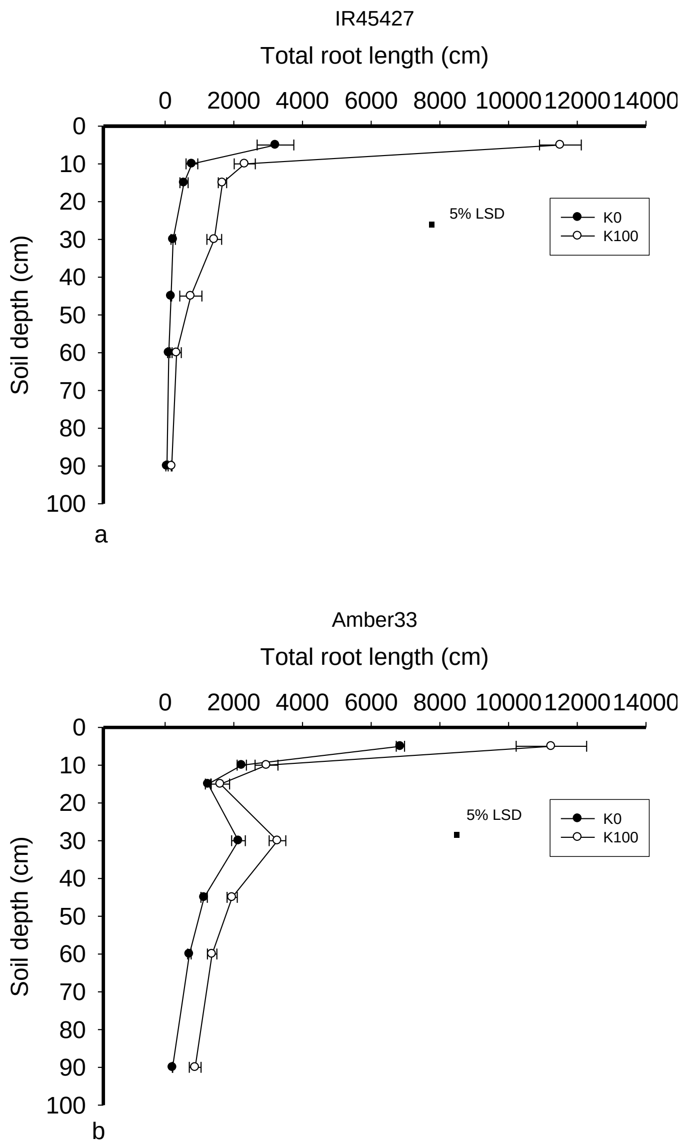


Figure 5.7 Effect of K application at rate of 100 kg/ha on root length of two rice (*Oryza sativa*) cultivars IR45427 (a) and Amber33 (b) grown in a glasshouse on a K responsive Black Vertosol. Values are the mean of 3 replicates with ± standard errors indicated by bars.

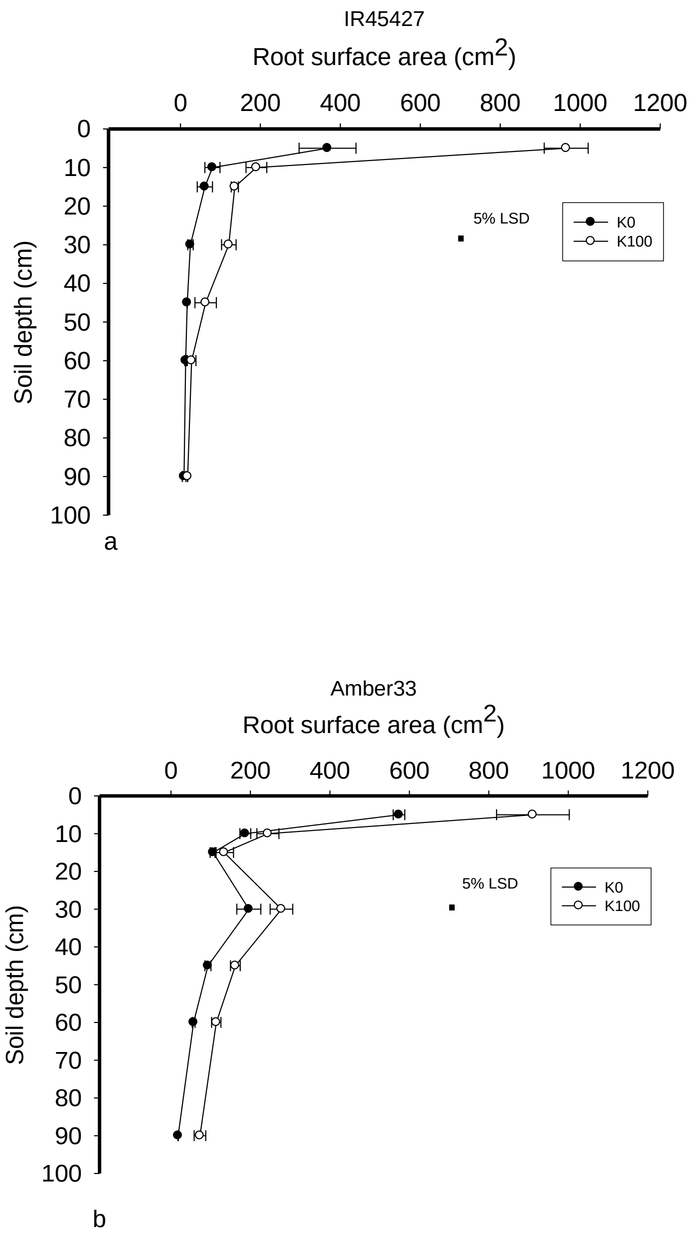
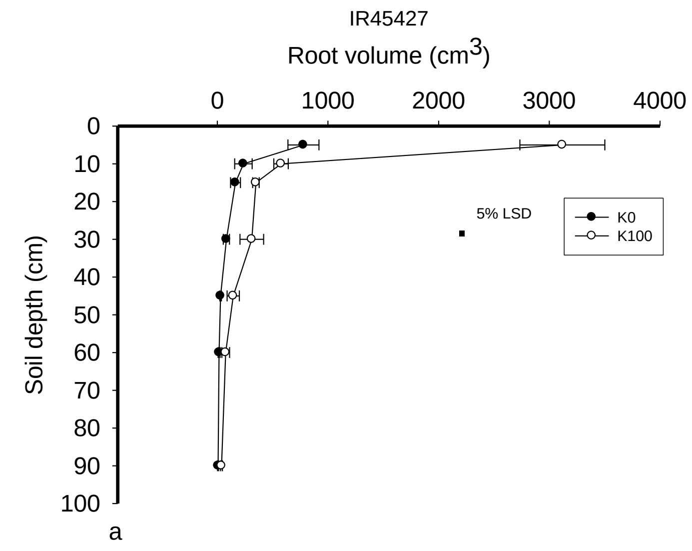


Figure 5.8 Effect of K application at rate of 100 kg/ha on root surface area of two rice (*Oryza sativa*) cultivars IR45427 (a) and Amber33 (b) grown in a glasshouse on a K responsive Black Vertosol. Values are the mean of 3 replicates with ± standard errors indicated by bars.



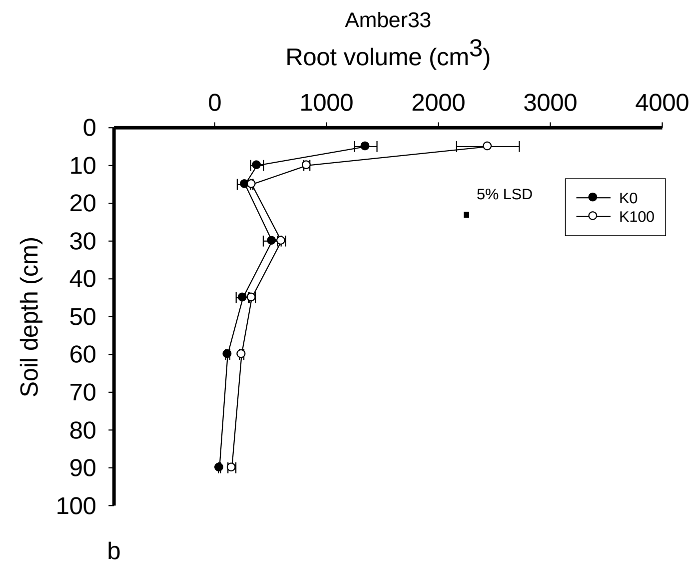


Figure 5.9 Effect of K application at rate of 100 kg/ha on root volume of two rice (*Oryza sativa*) cultivars IR45427 (a) and Amber33 (b) grown in a glasshouse on a K responsive Black Vertosol. Values are the mean of 3 replicates with ± standard errors indicated by bars.

Root length was greatest in the surface soil (Figure 5.10); a decrease in the RL was observed as depth increased. However, it was much lower in the no K-addition treatments. Root development was more extensive following K application with significant increases in RL, SA and RV throughout the whole rooting profile.

a b

Figure 5.10 Effect of K application at rates of 0 (a) and 100 kg/ha (b) on the root system of Amber33 grown for 150 DAT, in a glasshouse on a K responsive Black Vertosol at depth of 0 – 5 cm.

Root length density

There was significant ($P < 0.001$) cultivar-by-K rate interaction for root length density (RLD). RLD was high in the surface soil (0 – 5 cm) and declined with soil depth, but the extent of this decrease varied between the two cultivars (Table 5.4). The increase in surface RLD was nearly four times higher in IR45427 cultivar when supplied with K, than in Amber33. With K application, RLD in the whole profile, especially in the lower depth (60 – 90 cm), was higher than that in the control treatments.

Table 5.4 Effect of K application at 100kg/ha on root length density (cm root/cm^{3}soil) in two rice (*Oryza sativa*) cultivars grown on a K responsive Black Vertosol. Values are the mean of 3 replicates with ± standard errors of the means.

Soil depth (cm)	IR45427 Root length density (cm/cm^3)		Amber33 Root length density (cm/cm^3)	
	-K	+K	-K	+K
0-5	3.64±0.6	13.02±0.69	7.75±0.13	12.73±1.16
5-10	0.88±0.19	2.62±0.35	2.52±0.15	3.34±0.38
10-15	0.62±0.13	1.89±0.14	1.41±0.09	1.82±0.30
15-30	0.09±0.02	0.54±0.08	0.81±0.08	1.23±0.09
30-45	0.07±0.006	0.28±0.12	0.43±0.04	0.74±0.05
45-60	0.04±0.01	0.13±0.05	0.27±0.02	0.52±0.05
60-90	0.02±0.01	0.07±0.004	0.08±0.002	0.33±0.06
LSD (0.05)	**0.1**			

Root diameter

Application of 100 mg K/kg had minimal effect on root diameter in the surface soil with Amber33 but it increased root thickness in IR45427 by 24% ($P < 0.05$) (Table 5.5). The average root diameter increased by 34% in IR45427 and 35% in Amber33 when 100 mg K/kg was applied. Root diameter in Amber33 was 52% larger than the root diameter in IR45427.

Table 5.5 Effect of K application at rate of 100kg/ha on roots diameter (mm) of two rice (*Oryza sativa*) cultivars grown on a K responsive Black Vertosol. Values are the mean of 3 replicates with ± standard errors of the means of the means.

Soil depth (cm)	IR45427		Amber33	
	Root diameter (mm)			
	-K	+K	-K	+K
0-5	0.92±0.04	1.14±0.03	1.7±0.14	1.75±0.006
5-10	0.74±0.03	0.99±0.04	1.19±0.02	1.53±0.05
10-15	0.66±0.01	0.88±0.01	1.04±0.06	1.29±0.15
15-30	0.56±0.006	0.75±0.02	0.78±0.04	1.1±0.05
30-45	0.50±0.02	0.68±0.01	0.57±0.04	1.03±0.03
45-60	0.42±0.02	0.63±0.009	0.55±0.04	0.92±0.05
60-90	0.34±0.01	0.47±0.02	0.39±0.02	0.75±0.11
LSD (0.05)	**0.04**			
Average	0.59	0.79	0.89	1.20

5.4 Discussion

5.4.1 Agronomic characters

The above ground plant response to applied K was consistent with previous chapters (Sections 3.3.2 and 3.4.1). This chapter will add further details to examine the effect of K on root morphology.

5.4.2 Root parameters

The mean RL and RLD (Figure 5.7 and Table 5.4) were high following K-application in the surface soil depth of 0 – 5 cm. The mean RL and RLD of both rice cultivars decreased with soil depth, and were lower at all depths not receiving K-fertiliser. Potassium has been shown to enhance root growth and root penetration, which should result in better extraction of water and nutrients from the soil occupied by roots. From related studies on maize and wheat, Rasool *et al.* (2010) reported that K increased the growth and penetration of roots on sandy loam soil. Roshani and Narayanasamy (2010) also observed that K applied at a rate of 50 kg/ha (as the optimum amount, based on the test results) increased RL and RLD of wheat by 35%, 69 days after germination.

Root SA was also positively influenced by K addition, which translated into greater K uptake and translocation to shoots. This result is consistent with the observations that K-deficiency reduces RSA, and provides further evidence for the contention of Jia *et al.* (2008) that RSA is a strong indicator of K stress in rice. Shin *et al.*, (1995) identified a relationship between leaf surface area (LSA), photosynthesis and K uptake that may suggest a mechanism for variation in response to applied K based on aboveground plant parameters (Quampah *et al.* 2011). This might explain why IR45427 responded more to K application, resulting in higher grain yields than Amber33. This finding implies that K application is particularly mandatory for the dwarf cultivar (IR45427). However, all rice cultivars with increased RSA may benefit from better K nutrition (Kramer and Boyer 1995; Tang *et al*. 2007).

Root morphological parameters were reduced by up 38 – 82% in RL, 36 – 62% in RSA and 41 – 72% in RV under K limiting conditions. Jia *et al.* (2008) also observed a 12 – 52% reduction in root RL, 30 – 58% in RSA and 35 – 52% in RV under K limited conditions and application of K alleviated root biomass constraints. Increases in root biomass in response to K application occur not only in heavy clay Vertosol soils, but are also observed in lower CEC, sandy loam soils (Rasool *et al.* 2010) where the supply of K to the root surface is less likely to be constrained by low solution K activities. The rate of K application required to overcome root biomass constraints does vary with soil texture or CEC. In Jia *et al.* (2008) in a hydroponic culture, at the deficient level (5 mg K/l) all the recorded root morphology attributes were decreased significantly, and 40 mg/l rate of K was required to increase root biomass by 41 – 106%, whereas, in a range of cereals, Rasool *et al.* (2010) observed that 50 kg/ha rate of K was required in sandy loam texture soils. In contrast to many standard texts (Mengel and Kirkby 1982) on the effect of K application on plant growth, the magnitude of the effect on root biomass is often neglected, but, as can be seen in our data, and that of Jia *et al*. (2008) and Rasool *et al.* (2010) can be significant.

Root–shoot (R:S) ratios are lower under low K status (control) than under high K status (100 and 200 kg/ha) treatments due to greater root growth. The difference became larger with the increased growth duration (150 DAT) of the traditional taller cultivar (Amber33). In this experiment there was a 43% and 21% reduction in R:S ratios of IR45427 and Amber33, respectively under K limited conditions and application of K alleviated R:S ratio constraints. Hermans *et al.* (2006) reported insufficient K results in accumulation of sugars in source organs due to an inhibition in phloem loading for basipetal transport processes. The R:Ss of both IR45427 and Amber33 were increased by the application of K, suggesting enhanced biomass allocation to roots. Leaf surface area increased following K application and such a response occurred where more soil resources are needed to allow increased transpiration rates. This root-shoot relationship has been reported to greatly contribute to increased water uptake by the whole root system (Gowda *et al*. 2011; Woo *et al.* 2007).

Pots were flooded for most of the period of growth, and there was nothing limiting movement of water to a root surface. However, high water uptake is needed to compensate for the water loss by transpiration. Paddy rice, grown in completely flooded conditions, may show symptoms of water shortage if water uptake by roots cannot balance high transpirational water losses from the shoot (Miyamoto *et al.* 2001). Paddy rice roots are known to form constitutively large air spaces known as aerenchyma as a mechanism for coping with low oxygen concentrations. Uphoff and Randriamiharisoa (2002) reported that when rice plants are grown under constantly flooded conditions, much of the root cortex disintegrates to form aerenchyma. However, such air spaces can constitute a physical barrier to water movement across the root cylinder (Ranathunge *et al.* 2004). Potassium might modify the root system and increases water uptake in K-treated plants, resulting in the improvement of root growth and grain yields as demonstrated in this glasshouse experiment. As mentioned earlier (Section 2.3.1), K plays a key role in carbohydrate formation, a source of energy and rice plants spend alot of energy developing aerenchyma tissue in roots under continuous flooding.

As the experiment was focused on the possibility that fresh and dry root weights of experimental cultivars IR45427 and Amber33 might grow better in high K status soils, the results indicate that there are significant differences in root growth of the rice cultivars grown in soil fertilised with K, even with the same levels. This promotive effect of K was also in accordance with the findings of Wu *et al.* (2009) who reported that K increased root mass and root activity.

In both cultivars, added K fertiliser increased root distribution in the lower root regions. The results from this experiment indicate that the beneficial effect of K on root distribution up to the level of applied K (100 kg/ha); the effect of this level was greater than 200 kg K/ha, indicating that the extra fertiliser did not alter the distribution of root biomass. Both cultivars quickly grew roots to 90 cm depth with or without K application but with K application other parameters i.e., root length, surface area, volume and root diameter, increased at this depth significantly (Figures 5.7, 5.8, 5.9 and Table 5.5). Extension of roots below 40-50cm in this anaerobic system may have been facilitated by travel down the outside of the soil column, as indicated in Figure 5.2.

The vertical distribution of roots varied following K application. At < 60 cm depth root distribution increased by 400% in IR45427 and 155% in Amber33 compared to the control treatments.

However the proportion of roots allocated to individual layers following K application was not different. In essence, the K application promoted a more extensive, larger and deeper root system, rather than a change in the pattern of root allocation that favoured surface rooting over subsoil rooting. However, the healthier and deeper root system may play a critical role in preventing lodging. For example, Terashima *et al.* (1995) investigated the role of deeper rooting in increased resistance to lodging in rice and observed that although 13% of root system in the trial was in subsoil, it contributed > 50% of the resistance to basal lodging. In this study application of K increased the subsoil (10 – 90 cm soil depths) root mass by 22–100%, although the effects of lodging were not observed, probably because of the small nature of the pots used in the experiment. Under such conditions, there is minimal washing of surface soil away from the base of the plants as may happen under natural flooded conditions, which may predispose the plants to lodging.

These results demonstrate that root parameters in the semi-dwarf cultivar (IR45427) were more responsive than those of the taller cultivar (Amber33) most likely due to variation in shoot growth (Figure 5.3d). The increased allocation of carbohydrate to shoot biomass when supplied with K in the taller cultivar resulted in smaller changes in root biomass allocation. Semi-dwarf cultivars have thicker stems and stronger straw stiffness and are therefore expected to have a greater resistance against root and stem lodging as reported by Berry *et al.* (2003).

5.5 Conclusion

All the above information suggests that K application significantly increased root parameters, namely RL, RSA, RV, RDM, RLD, RMD, RSR, RB and RD, thus, support large root system which is very important for absorption of water and nutrients and for plant anchorage. Addition of K might be one possible means of increasing rice resistance to lodging and increasing rice productivity. The absence of root lodging was observed under the control treatment in the glasshouse experiment likely due to the flooded soil was kept in place by the plastic pots. Under the field conditions, the washing a way of the soil from rice plant roots enhances lodging. Further field research is needed to develop appropriate K fertiliser rates for reducing susceptibility of rice cultivar such as Amber33 to lodging with proven economic benefits to farmers in Iraq.

CHAPTER 6: **POTASSIUM AND RICE WITH HIGH N UNDER FIELD CONDITIONS**

6.1 Introduction

Rice (*Oryza sativa*.L) is one of the most important cereal crops in Iraq and the supply is critical for food security. Farmers grow rice in most districts of Najaf and Al Diwaniyah provinces and cultivate rice in 70% of the potential area. Farmers rarely use organic fertilisers, but depend on chemical fertilisers such as urea and DAP. There is no addition of K fertiliser and substantial removal of straw from rice fields will have resulted in continuing soil K depletion and rapid expansion of K deficient areas (Ministry of Planning 2007).

Traditional thought is that Iraqi soils are generally rich in K however it is likely that after years of removal Iraqi soils now need urgent supplementation with external K sources (Al-Zubaidi 2004).

Growing rice in Iraq in the traditional way involves several steps starting with soil preparation by cultivation, and then followed by transplanting rice seedlings into the puddled soil to grow the crop in a flooded condition. The traditional irrigation technique used in Iraq as a part of planting process consumes large amounts of water, in a country where a third of the population depends on farming. Water shortages are an ongoing problem in addition to increased salinity; most likely the result of flooding. Salinity also reduces the quality of irrigation water. All of these factors have caused a marked decline in the sustainability of cultivated lands. In order to better understand the productivity and nutrition of rice plant under Iraqi conditions, two experiments were conducted under flood irrigation during the summer of 2010 on clay loam soils in two locations (Najaf and Al

Diwaniyah provinces), as well as a small demonstration with a single replicate in a private field in the Ash Shamiyah district, Al Diwaniyah province, Iraq.

6.2 Objective of the study

The aim of this study was to determine the effects of K fertiliser on rice yield, using split applications to ensure that there was adequate K fertilisation throughout growth for Iraqi rice production. Field experiments to assess rice responses to K fertilisation were undertaken in two locations with differing soils and environmental conditions. The aim of this field study was to assess the value of added K fertilisation for yield and lodging improvement under commonly used commercial conditions.

6.3 Methods

6.3.1 Study sites

The three study sites were located in Mashkhab, Al-Najaf province, (latitude: 32°0′1.728″N, longitude: 44°19′51.0204″E) (Figure 6.1). Najaf is at the edge of the western desert in Iraq; it is dry and hot in summer and colder and drier in winter. Najaf is approximately 53 m above sea level and about 160 km from Baghdad. Al Diwaniyah (latitude: 31°58′41.16″N, longitude: 44°53′59.28″E) has sedimentary soils; it is dusty, hot, and dry in summer, but wet, cold, and muddy in the winter. It is approximately 23 m above sea level and about 180 km from Baghdad (Figure 6.1).

Figure 6.1 Location of Najaf and Al Diwaniyah provinces

A demonstration experiment with a single replicate was carried out in the Ash Shamiyah district (latitude: 31°58′1.2″N, longitude: 44°36′14.4″E), Al Diwaniyah province during 2010-2011. The field had a clay loam textured soil. Details of some soil characteristics for each of the three locations are shown in Table 6.1.

Potassium was applied at two levels (0 and 200 kg/ha as potassium sulphate), with the common commercial application rate of 200 kg/ha N as urea, 50 kg/ha P and 20 kg/ha S as calcium phosphate and gypsum, respectively.

6.3.2 Seeds source and germination

The rice seeds of IR52713 were supplied by the Yanco Agricultural Institute, Australia and those of Amber33 were supplied by the Rice Research Station in Iraq. Rice seeds (cvs. Amber33 and IR52713) were soaked (1 day), incubated (2 days), covered with cloth (5 days) and then planted in nursery plots measuring 30 × 60 cm (12 days) (Figure 6.2). 20 day old seedlings of Amber33 and IR52713 were then transplanted in July, 2010, into the experimental plots. The seedlings were spaced 25×20 cm. After transplanting, 10 cm water depth was maintained in the experimental plots. The crop was harvested when 80% of grains were yellow in November 2010.

Figure 6.2 Rice (*Oryza sativa*) grown in nursery plots, Najaf, June 2010.

6.3.3 Experiment design

A randomized complete block design (RCBD) field experiment was conducted in the 2010 – 2011 season at the Najaf and Al Diwaniyah sites in irrigated fields. The experiments were laid out in micro plots with bunds between the plots (3×3 m^2) with two cultivars and two levels of K (0 and 200 kg/ha). Each treatment was replicated three times. A single replicate with one cultivar was used in the Ash Shamiyah location using the same plot area and K levels. Results were analysed (except Ash Shamiyah location) by analysis of variance (ANOVA) using R statistical package (R Development Core Team 2009) and significant results were assessed as equal to or greater than P=0.05. Results were graphed using SigmaPlot, v.7.

6.3.4 Fertiliser application

The rice cultivars were supplied with 200 kg N/ha soil as urea (CO $(NH_2)_2$) (46% N) and DAP (18% N+20%P). Potassium was added to the soils at 200 kg K/ha as K_2SO_4 (45% K) at a rate of 200 kg/ha as a split application with 100 kg/ha before sowing and 100 kg/ha at 35 days after transplanting (DAT) at the Najaf and Al Diwaniyah locations. Nitrogen was applied in two split applications as 100 kg/ha at 7 DAT with the remaining N applied at 35 DAT. In addition, P fertiliser was applied to all plots before transplanting once as an upfront dose of 50 kg P/ha as calcium tetra hydrogen di-orthophosphate Ca $(H_2PO_4)_2$ (24%P). A basal treatment of 20 kg S/ha was applied as gypsum to all treatments.

6.3.5 Weed control

The most important weeds of rice in Iraq include Nutgrass (*Cyperus rotundus L.),* Calin gale (*Cyperus ordoratus L.),* Barnyard grass (*Echinochloa crus-galli L.*), Sabat (*Diplanche fuscua*) and Panic grass (*Echinochloa colonum L.),* which can cause serious yield reductions (Ekeleme *et al.* 2007). Weed control was done manually as necessary during the season, when weeds were observed.

6.3.6 Sampling

Soil samples from 0 – 10 and 10 – 30 cm depths were collected post-harvest from all treatment plots. Samples were labeled, air-dried, and ground to less than 2 mm. Shoots were harvested manually 15 – 20 cm above ground level, and separated into grains and straw. The straw was dried at 40 °C for 72 h. The grain was spread in the sun to reduce moisture content. After drying, shoots and grains were collected, and ground to less than 2 mm. Samples were air freighted to Australia, where they were subjected to gamma radiation in quarantine, and then sent to the UNE laboratory with weighing before analysis.

Measurement of plant parameters

Plant samples were collected from the plots at the flowering and harvest stages. Post-harvest, grain samples were also collected for analysis. The plant measurements were;

(1) Plant height (cm) was measured before harvest as the average height of 10 plants from the base of the plant to the tip of the tallest panicle.

(2) Panicle length (cm) at harvest at Najaf was randomly assessed for 10 plants from the panicle base to the panicle tip.

(3) Grain yield per plot after drying to approximately 14% moisture. Grains then were winnowed to clean the remaining chaff and trash, and yield was determined according to the following equation;

$$\frac{\text{Yield per plot(kg)}}{\text{Harvest area }(\text{m}^2)} \times \frac{\text{Moisture(adjustment)}}{1000} \times 10000$$

(4) 1000-grain weight (g) (Najaf only) was the average weight of 1000 filled kernels, which were selected at random after oven drying at about 14% moisture content.

(5) Number of filled grains per panicle (Najaf only) was counted using 10 sample panicles taken at random.

(6) Number of panicles per square meter (Najaf only) was the number of panicles on the 10 plants times 2 excluding any panicles having less than five seeds.

(7) Harvest index was calculated by using the following formula.

$$\mathrm{HI} = \frac{\text{Grain yield}}{\text{Biological yield}} \times 100$$

Plant and soil analysis

Plant samples were digested using the sealed chamber digestion method of Anderson and Henderson (1986). In brief, approximately 0.2 g of ground plant material from each sample was predigested with a mixture of 70% $HClO_4$ and 30% H_2O_2 (v/v) overnight, then placed in an oven at 80˚C for 30 minutes. Samples were repeatedly digested with hydrogen peroxide until the solutions were clear, filtered, made to volume and cations were measured using inductively coupled plasma atomic emission spectroscopy ICP-AES. Exchangeable bases were extracted with 1 M NH4Cl adjusted to pH 8.5 with 20% NH_4OH, and Ca, Mg, K, and Na measured by ICP-AES and effective CEC determined (Rayment and Higginson 1992).

6.4 The variation in temperature (˚C) during the experimental season in Najaf and Al Diwaniyah.

Air temperature and humidity were measured using standard meteorological methods. Maximum temperatures ranged between 28.4 – 46 ºC in Najaf and between 28.4 – 49.8 ºC at Al Diwaniyah during the 2010 season (Figure 6.3a and b). Humidity ranged from 40 – 85% in the two locations.

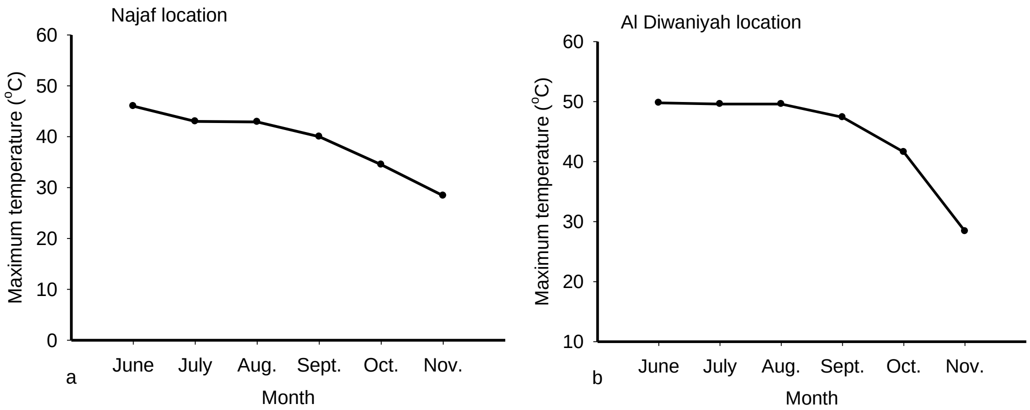


Figure 6.3 The variation in temperature (°C) during 2010 season for (a) Najaf and (b) Al Diwaniyah.

6.5 Results

Selected physical and chemical properties of the study sites before fertiliser treatments were applied are presented in Table 6.1 to assess the nutritional status of the experimental sites.

Table 6.1 Selected soil physical and chemical properties of soils, Iraq.

Location	Soil depth (cm)	pH[a]	EC[b] (dS/m) Initial	post-harvest	Soil texture [c]
Najaf	0–20	7.6	4.3	3.3	Clay loam
Al Diwaniyah	0–20	8.0	11.5	5.5	Clay loam
Ash Shamiyah	0–20	8.1	6.1	4.7	Clay loam

[a] 1:5 soil/water suspension; [b] 1:5 soil/water extract; c hydrometer method

6.5.1 Effect of K application on K concentration in soils.

Additions of K to the soil at 200 kg/ha significantly ($P < 0.05$) increased the concentrations of soil K at Najaf and Al Diwaniyah at depths of 0 – 10 and 10 – 30 cm. The results are shown in Table 6.2. Soil K content ranged from 0.35 to 0.44 $cmol_c$/kg in Najaf and from 0.35 to 0.39 $cmol_c$/kg in Al Diwaniyah in the treatments receiving no K fertilisers, compared to the soil K content of 0.40 – 0.82 $cmol_c$/kg and 0.55 – 0.72 $cmol_c$/kg in Najaf and Al Diwaniyah, respectively in the treatments when K was applied. There was no effect of K application on cation exchangeable capacity (CEC) at either location.

Table 6.2 Effect of K application (no potassium vs 200 kg K/ha) on K concentration and ECEC ($cmol_c$/kg) in soils of two rice (*Oryza sativa*) cultivars grown on a K responsive clay loam soil. Values are the mean of 3 replicates with ± standard errors of the means, Najaf and Al Diwaniyah.

Location	Cultivar	Depth (cm)	K status	K Conc. ($cmol_c$/kg)	CEC $cmol_c$/kg
Najaf	IR52713	0 -10	-K	0.39±0.003	12.66±0.63
		10-30	-K	0.35±0.03	12.46±0.99
		0 -10	+K	0.82±0.35	13.40±0.86
		10-30	+K	0.40±0.03	12.47±0.48
	Amber33	0 -10	-K	0.44±0.01	13.26±0.46
		10-30	-K	0.35±0.03	13.06±0.46
		0 -10	+K	0.59±0.01	14.37±1.00
		10-30	+K	0.53±0.01	13.47±0.26
LSD (0.05)				**0.10**	**NS**
Al Diwaniyah	IR52713	0 -10	-K	0.42±0.07	13.53±1.37
		10-30	-K	0.35±0.03	13.06±0.70
		0 -10	+K	0.72±0.04	13.27±0.13
		10-30	+K	0.58±0.01	13.50±0.53
	Amber33	0 -10	-K	0.38±0.02	13.33±0.40
		10-30	-K	0.37±0.04	13.00±0.57
		0 -10	+K	0.65±0.04	13.93±1.38
		10-30	+K	0.55±0.06	15.76±2.70
LSD (0.05)				**0.07**	**NS**

6.5.2 Effect of K application on K concentration in grain and straw.

Potassium concentration (%) in rice shoots (leaf plus stem) significantly ($P < 0.01$) increased with added K at the flowering and harvest stages (Table 6.3). In Najaf, lower concentrations of K in plant tissues were recorded in the zero K treatment (control) at flowering in both cultivars compared to when K fertiliser was applied. A similar trend was observed at the harvest stage, with a significant ($P < 0.001$) increase of 19 and 31% over the control in IR52713 and Amber33, respectively, with K application. An increase in K concentration of rice grains was also significant ($P < 0.01$). The effect of cultivar on this trait was also highly significant ($P < 0.001$); an increase over the non-K treatment by 22 and 10% was observed in IR52713 and Amber33, respectively.

At Al Diwaniyah, the K concentration in shoots at flowering increased by 19 and 16% over control in IR52713 and Amber33, respectively with K application. At harvest this increased to 27% in IR52713 and 17% in Amber33 by the application of K. Similarly, grain K concentration increased by 55 and 16% over the control in IR52713 and Amber33, respectively when K was applied.

Table 6.3 Effect of K application (no potassium vs 200 kg K/ha) on K concentration (%) shoot (leaves plus stems) of two rice (*Oryza sativa*) cultivars grown on a K responsive clay loam soil. Values are the mean of 3 replicates with ± standard errors of the means, Najaf and Al Diwaniyah.

Location	Cultivar	K status	K Conc. (%) in shoot (leaves + stems) at flowering	K Conc. (%) in shoot (leaves + stems) at harvest	K Conc. in grain (%)
Najaf	IR52713	-K	1.51±0.03	1.20±0.03	0.23±0.006
		+K	1.57±0.05	1.43±0.06	0.28±0.01
	Amber33	-K	1.48±0.04	1.05±0.11	0.31±0.003
		+K	1.73±0.02	1.37±0.10	0.33±0.01
LSD (0.05)			**0.08**	**0.19**	**0.01**
Al Diwaniyah	IR52713	-K	1.37±0.05	1.00±0.06	0.29±0.09
		+K	1.63±0.03	1.27±0.04	0.45±0.03
	Amber33	-K	1.34±0.04	1.18±0.03	0.51±0.03
		+K	1.55±0.09	1.38±0.03	0.59±0.02
LSD (0.05)			**0.10**	**0.09**	**0.11**

6.5.3 Effect of K application on K uptake by grain and straw

Potassium uptake significantly ($P < 0.01$) increased in both grain and straw yields with K application at Najaf (Table 6.4). There was a significant ($P < 0.05$) effect of cultivar on these parameters. In IR52713 there was an increase of 55 and 62% in K uptake by grain and straw, respectively. Similarly, there was an increase of 33 and 63% in K uptake by grain and straw, respectively in Amber33 when K was applied. At Al Diwaniyah, there is an interaction between cultivar and K treatment with a P value = 0.039 for K uptake by grain. Potassium uptake of grain increased by 497 and 106% over the control in IR52713 and Amber33, respectively. Straw yields significantly ($P < 0.001$) increased by 45% and 91% in IR52713 and Amber33, respectively when K was applied.

Table 6.4 Effect of K application (no potassium vs 200 kg K/ha) on K uptake (kg/ha) of two rice (*Oryza sativa*) cultivars grown on a K responsive clay loam soil. Values are the mean of 3 replicates with ± standard errors of the means, Najaf and Al Diwaniyah.

Location	Cultivar	K status	K uptake by grain (kg/ha)	K uptake by straw (kg/ha)
Najaf	IR52713	-K	10.5±1.0	50.6±6.6
		+K	16.3±1.2	81.8±8.4
	Amber33	-K	14.7±0.5	75.9±17.0
		+K	19.6±2.0	123.7±3.7
LSD (0.05)			**3.0**	**23.6**
Al Diwaniyah	IR52713	-K	0.62±0.2	43.3±2.7
		+K	3.7±0.2	62.8±1.4
	Amber33	-K	6.8±0.5	44.2±2.2
		+K	14±1.6	84.5±9.7
LSD (0.05)			**1.9**	**12.1**

6.5.4 Plant height (Najaf only)

Both cultivars responded to extra K in the same way (Figure 6.4). Amber33 was the taller cultivar and only marginal increases in height occurred with added K in both cultivars.

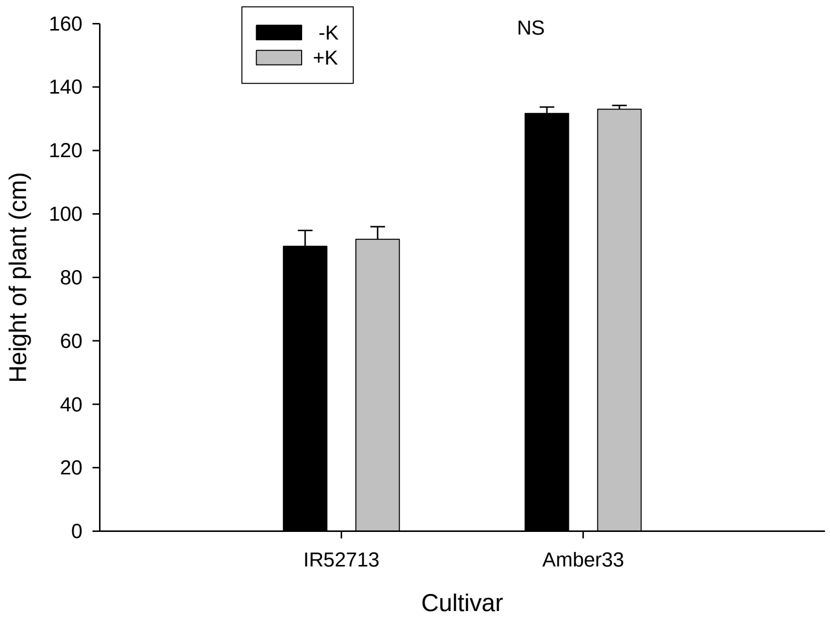


Figure 6.4 Effect of K application (no potassium vs 200 kg K/ha) on height of plant per m^2 of two rice (*Oryza sativa*) cultivars grown on a K responsive clay loam soil. Values are the mean of 3 replicates, with ± standard error indicated by bars, Najaf.

6.5.5 Grain yield and yield components: Najaf and Al Diwaniyah locations

6.5.5.1 **Grain yield**

Grain yield (GY) was significantly ($P < 0.001$) increased by K application (Figure 6.5). At Najaf, grain yield increased by 1.2 t/ha in both cultivars following K application. At Al Diwaniyah, grain yield showed marked increases ($P < 0.001$) following K application in both cultivars. Without K, IR52713 had a very low grain yield and it only increased slightly with added K. Conversely, without K Amber33 had a higher yield than IR52713 with K and it showed a marked increase in yield with K. Overall, yields were much higher at Najaf than at Al Diwaniyah.

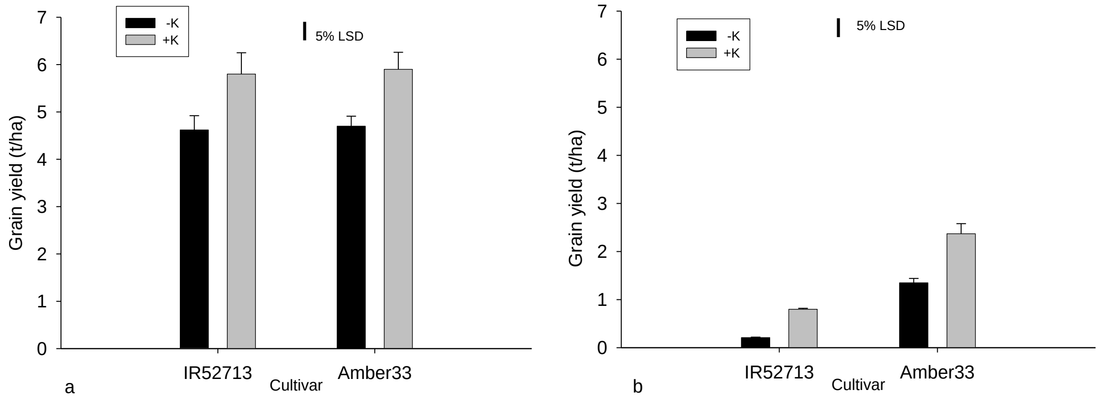


Figure 6.5 Effect of K application (no potassium vs 200 kg K/ha) on grain yield (t/ha) of two rice (*Oryza sativa*) cultivars grown on a K responsive clay loam soil. Values are the mean of 3 replicates, with ± standard error indicated by bars, for (a) Najaf and (b) Al Diwaniyah.

6.5.5.2 **Straw yield**

As for grain yield, K fertiliser significantly (P < 0.05) increased rice straw yield (Figure 6.6). Straw yield increased with added K by 1.9 t/ha in Amber33 and by 1.5 t/ha in IR52713 at Najaf. At Al Diwaniyah, added K again increased straw yield in both cultivars but this effect was greatest in Amber33 (P value 0.016). Straw yields were greatest in Amber33 at Najaf and similar to IR52714 at Al Diwaniyah.

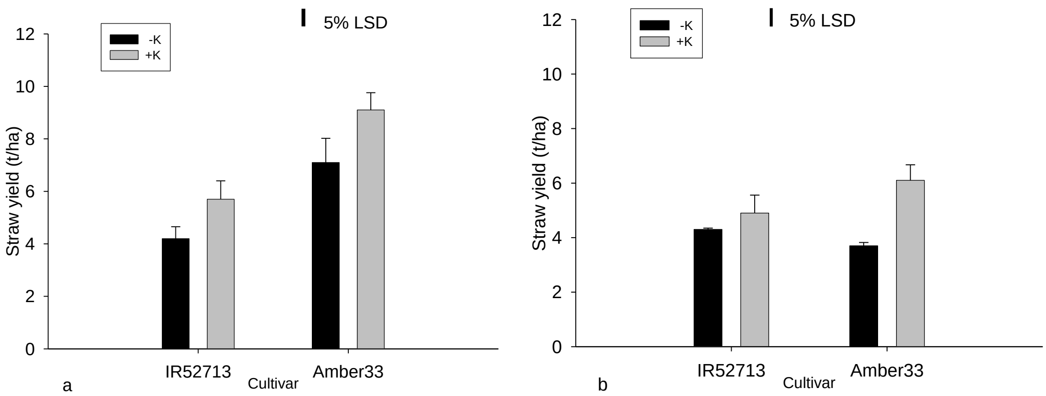


Figure 6.6 Effect of K application (no potassium vs 200 kg K/ha) on straw yield (t/ha) of two rice (*Oryza sativa*) cultivars grown on a K responsive clay loam soil. Values are the mean of 3 replicates, with ± standard errors indicated by bars, for (a) Najaf and (b) Al Diwaniyah.

As would be expected, IR52713 had a higher HI than Amber33 but there was no effect of K on HI in either cultivar at Najaf. At Al Diwaniyah, harvest index was relatively low in IR52713 and showed a strong increase (P < 0.001) with added K. However, HI was much higher with Amber33 and in this cultivar added K had little effect on HI (Figure 6.7). Without added K IR52713 had a very low HI at Al Diwaniyah.

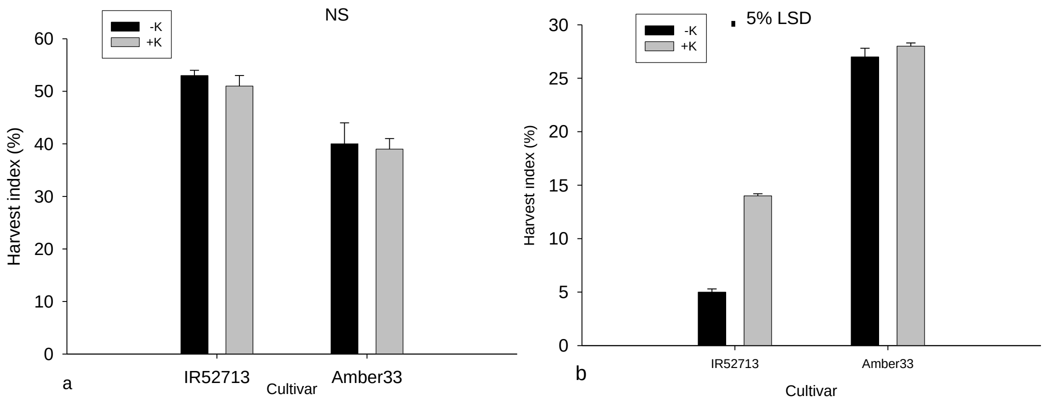


Figure 6.7 Effect of K application (no potassium vs 200 kg K/ha) on harvest index (%) of two rice (*Oryza sativa*) cultivars grown on a K responsive clay loam soil. Values are the mean of 3 replicates with ± standard errors indicated by bars, (a) Najaf, and (b) Al Diwaniyah.

6.5.5.3 **Number of filled grain and panicle length (Najaf only)**

Both cultivars responded to extra K in a similar way in terms of grains per panicle. A borderline significant (P=0.09) trend was noted for the effect of K on the number of filled grain per panicle: an increase of 9 and 16% was observed of IR52713 and Amber33, respectively, when K was applied (Figure 6.8). No significant effect of K on the panicle length was observed, although Amber33 had longer panicles (P < 0.001) (Figure 6.9).

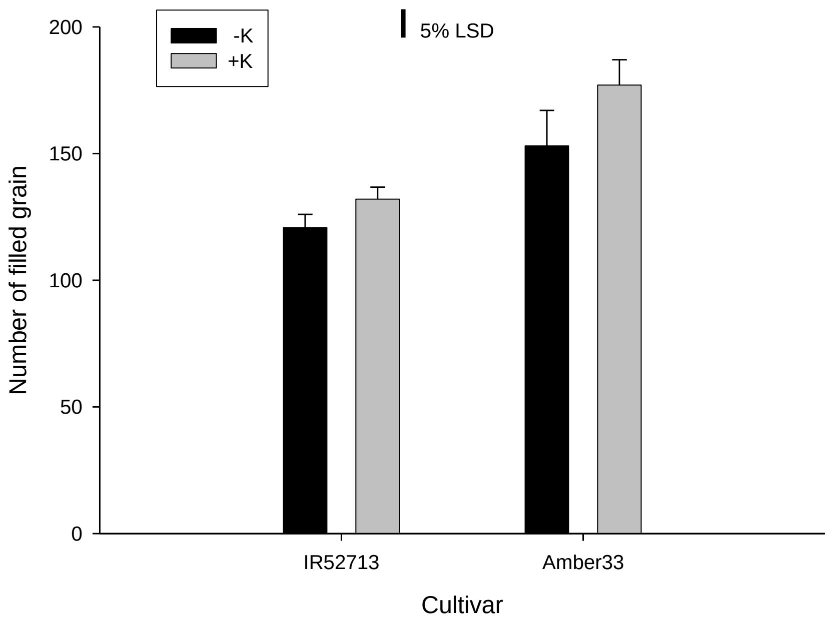


Figure 6.8 Effect of K application (no potassium vs 200 kg K/ha) on number of filled grain per panicle of two rice (*Oryza sativa*) cultivars grown on a K responsive clay loam soil. Values are the mean of 3 replicates, with ± standard error indicated by bars, Najaf.

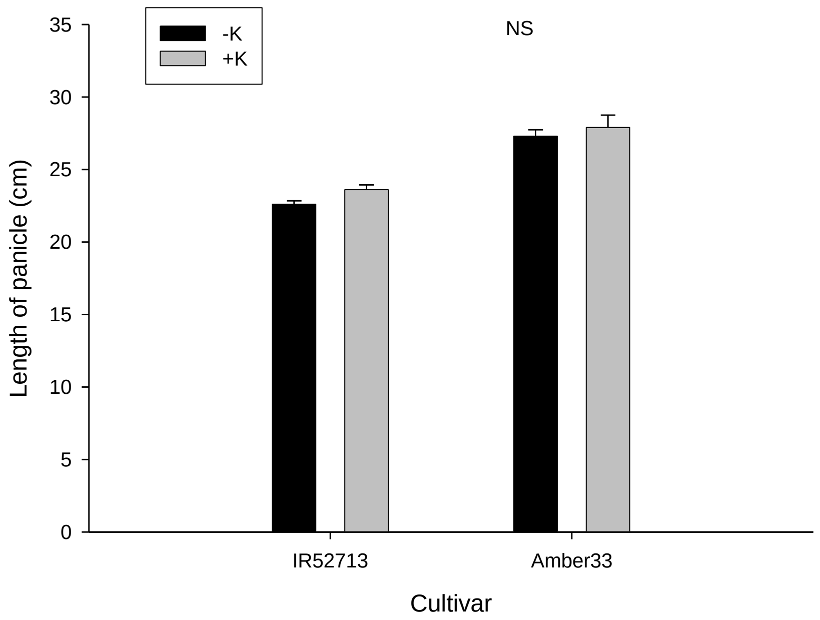


Figure 6.9 Effect of K application (no potassium vs 200 kg K/ha) on panicle length of two rice (*Oryza sativa*) cultivars grown on a K responsive clay loam soil. Values are the mean of 3 replicates with ± standard error indicated by bars, with standard error indicated by bars, Najaf.

6.5.5.4 **Number of panicles per m2 (Najaf only)**

Number of panicle per m^2 was significantly ($P < 0.05$) increased by K application in both cultivars (Figure 6.10).

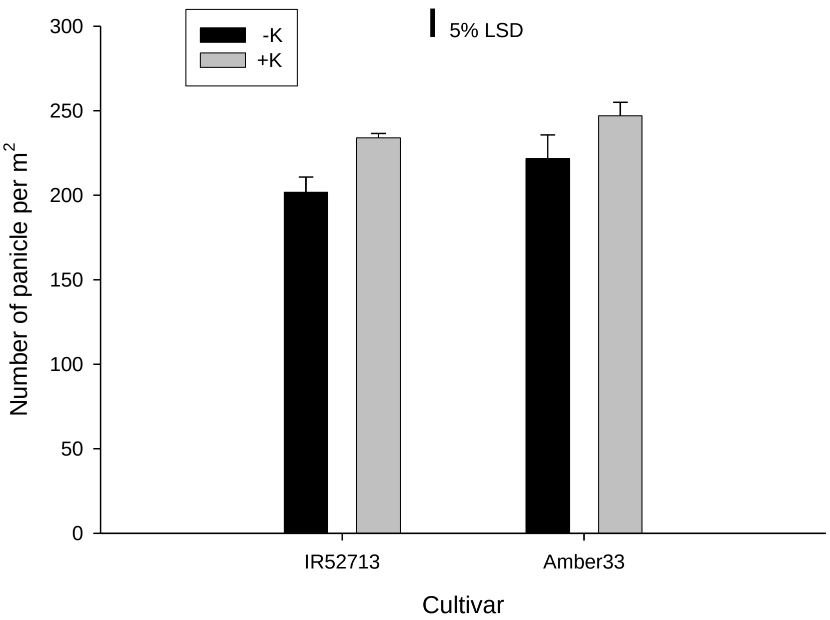


Figure 6.10 Effect of K application (no potassium vs 200 kg K/ha) on number of panicles per m^2 of two rice (*Oryza sativa*) cultivars grown on a K responsive clay loam soil. Values are the mean of 3 replicates, with ± standard error indicated by bars, Najaf.

6.5.5.5 **One thousand-grain weight (Najaf only)**

Added K increased ($P < 0.05$) 1000 grain weight in both cultivars with IR52713 having larger grains (Figure 6.11).

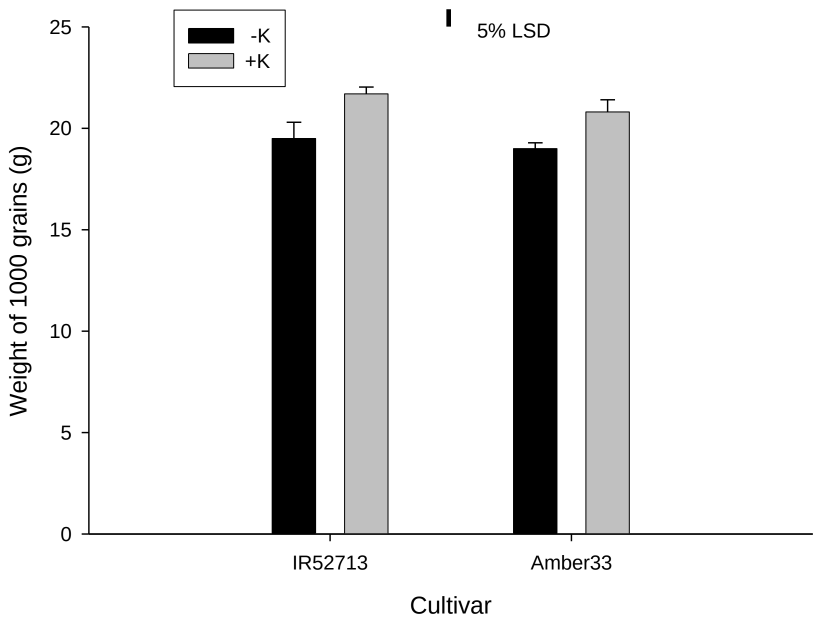


Figure 6.11 Effect of K application (no potassium vs 200 kg K/ha) on weight of 1000 grains of two rice (*Oryza sativa*) cultivars on a K responsive clay loam soil. Values are the mean of 3 replicates, with ± standard error indicated by bars, Najaf location.

6.5.6 Ash Shamiyah location

Further evidence that rice responds well to K application occurred in the single replicate demonstration at Ash Shamiyah (Figure 6.12). Added K also appeared to reduce lodging in the field. A grain yield of 6.1 t/ha with a straw yield 7.4 t/ha were produced when 200 kg K/ha was applied, whereas only 3.2 t/ha grain yield and 5.5 t/h straw were obtained from the control treatment (no K-fertiliser). Harvest index increased 24% over the control due to K application.

Figure 6.12 Effect of K application (no potassium vs 200 kg K/ha) on lodging of rice (*Oryza sativa*) cultivar Amber33 grown for 150 DAS, in a field on a K responsive clay loam soil, Ash Shamiyah location, Al Diwaniyah province, Iraq.

The soil K level was 0.40 $cmol_c$/kg in a CEC of 13.7 $cmol_c$/kg. However, the application of K at 200 kg/ha rate increased K concentration to 0.70 $cmol_c$/kg in a CEC of 14.1 $cmol_c$/kg in the surface soil. Potassium uptake by the grain was 9 kg/ha in the control treatment whilst it was 24 kg/ha when K was applied.

6.6 Discussion

Much of the current rice crop in Iraq is grown in the Najaf location (about 38% of the rice cultivated area) and whilst K fertiliser increased grain yields there was little difference in the performance of the two cultivars. In contrast at Al Diwaniyah, with much more stressful growing conditions, the mean grain yield of Amber33 was 196% higher than IR52713. However, IR52713 did increase its yield by 281% when K was added but this cultivar was poorly adapted to stressful environments. The Al Diwaniyah experimental site had high salinity, high temperatures (48 ^{o}C) during flowering and some bird damage. Added K fertiliser was able to reduce the negative effects of this stress and maintain yield increases as it did at Najaf. One likely mechanism for K application to improve yield is the known role of K in maintaining leaf turgor through stomatal control. Rice plants with better stomatal control are likely to be more water efficient in hot and dry conditions. Whilst Amber33 was better adapted to these conditions (especially high levels of salinity), farmers do not grow rice traditionally in regions such as Al Diwaniyah since overall yields are relatively low.

Interestingly, the marked depression in grain yields at Al Diwaniyah was less evident in straw production and this resulted in very poor HI figures for IR52713 especially without added K. Amber33 appeared to maintain relatively stable HI figures across the two locations whilst IR52713 achieved good HI figures of 50% plus under good growing conditions at Najaf.

Increasing rates of K from 0 to 200 kg/ha increased the rice straw dry matter yield (Figure 6.6 and Section 6.5.6). As indicated and discussed in earlier studies (Section 5.3.1 and Sections 3.3.2 and 3.4.1) under glasshouse conditions, the positive effects of K on plant height, number of tillers, stem thickness, resulted in high straw yield. The grain yield increase following K application (Figure 6.5) was related to the effects of K on the main yield components (number of panicle per square meter, a very important component of yield (Ahmad *et al.* 2005), 1000-grain weight and the number of filled grain/unit area); these findings are in agreement with the results presented by Brohi *et al.* (2000) on rice straw yield and by Bohra and Doerffling (1993) on grain yield.

1000 grain weight (TGW) is mainly a genetically controlled property and differs from one cultivar to another. Some researchers (i.e. Bahmaniar and Ranjbar 2007b) believe that K fertiliser can cause an increase in 1000 grain weight. In this experiment the TGW was increased and although further work is needed it suggests that adequate K application may produce heavier grained rice (Din *et al.* 2001).

In this study, as would be expected, K concentrations in both the soil and plants increased with increasing K fertilisation (Tables 6.2 and 6.3). Soil K content in Najaf and Al Diwaniyah locations, was critical or close to reported critical values (0.08 – 0.41 $cmol_c$/kg) for semi-arid and arid regions of Asia (Doberman *et al.* 1996c). Cation exchange capacity (CEC) at the experimental sites ranged between 12.5 and 15.8 $cmol_c$/kg which is at the lower end of common Iraqi soil figures (10 – > 40 $cmol_c$/kg) (Yousef *et al.* 1987). Soils with relatively low CEC levels are likely to be subject to leaching. Soil K concentrations near 0.4 $cmol_c$/kg would not normally be considered K responsive in Australian conditions, particularly in soils with relatively low CEC. However the higher soil salinity and the presence of 2:1 clay minerals which may increase K fixation may reduce the K concentration and activity in soil solution (Dobermann and Fairhurst 2000). This result is in agreement with similar observations by Al-Zubaidi (2004) who mentioned that beidillite (a member of the smectite family) occurs in most Iraqi soils including the study sites.

Plant straw K content at harvest ranged from 1 – 1.43%, which is close to the typical observed range (1.17 – 1.68%) and the observed average (1.39%) (Table 2.2) of the modern rice cultivars (n=1300) in Asia (Dobermann and Fairhurst 2000). However, these values are less than the average value of 1.74%, which was observed in the north of California, US by Nader and Robinson (2004) in rice straw collected at several locations. Low K concentrations may result from the large quantities of K that are extracted from these soils by intensive cropping systems (Panaullah *et al.* 2006), and/or to the leaching of K from these soils due to the flooding during the rice-growing season (Dobermann and Fairhurst 2000).

In general, rice straw is rich in K and the increased export of nutrients by rice straw removal will have reduced soil K content. In the present experiments K removal by rice was 3.6 –16.3 kg/ha in the grain and 43.3 – 123.7 kg/ha in the straw (Table 6.4). Increasing SOM levels by practices such as returning rice straw back to the field or using legume crops in rotation could assist in improving soil fertility (Tuyen *et al.* 2006).

Retention of the rice straw could have positive effects on the soil K balance on clay loam soils to improve the long-term K balance in the rice-wheat cropping system (Panaullah *et al.* 2006), which is a common practice in Iraq. Currently rice straw is widely cut and removed from paddock by farmers for feeding animals. Straw can be recycled either by direct incorporation after the first ploughing or by spreading it on the surface of the land. The K present in straw can supply K to the growing rice crop (Amarasiri and Wickramasinghe 1984). This would represent a significant change to the farming system however, as alternative feed sources, with better nutritional properties, would need to be sourced.

Grain K contents exceeded the range of values (Table 6.3) determined by Dobermann and Fairhurst (2000); this may have been related to the use of different cultivars and a relatively high K application rate.

Despite the results of our previous experiments showing that plant height of rice was increased with K application in the glasshouse, no effect of K fertiliser on plant height was observed in the field experiments. It may be because of difference in the volume of soil accessed by each plant (in the field plant roots can access a greater volume of soil and so uptake more K) or possibly the temperature difference between glasshouse and field affected K uptake and also the rate of plant growth.

The demonstration site at Ash Shamiyah provided some visual evidence that K application reduced lodging. Owing to logistical difficulties no other lodging measurements were possible in these field experiments. This is one area which will need further work in the field in Iraq.

6.7 Conclusions

Limited evidence suggest that a basal application of 100 kg K/ha and top dressing with a further 100 kg K/ha 35 DAT increased rice resistance to lodging especially in the lodging susceptible Amber33 cultivar.

These field experiments indicate an ability for K fertiliser to both increase rice grain and straw yields but equally importantly to mitigate the adverse effects of a range of environmental stresses which reduce rice yields. These effects need further field verification.

In a glasshouse experiment, it was observed that 100 kg K/ha was as effective as 200 kg K/ha in terms of root growth parameters. Further studies are needed to evaluate rice resistance to lodging and grain yield at this rate (100 kg K/ha). Straw retention in the field might be a key strategy to recycle K as > 50% of the K taken up by rice plants ends up in the straw. This would reduce not only the use of mineral fertilisers but also have a positive effect on soil physical properties.

CHAPTER 7: **SUMMARY AND FURTHER STUDIES**

7.1 Summary and further studies

7.1.1 Summary

Rice (*Oryza sativa*.L) is one of the major cereal crops in Iraq and important for food security. The productivity of the most common Iraqi rice cultivar, Amber33, (2.9 t/ha) may be improved through basic improvements in soil fertility and agronomy. The effect of applied K in clay loam soil on irrigated rice production has been studied in a series of experiments. It is evident from the results of these investigations that the applied K in soils testing low in available K has a most pronounced effect on irrigated rice production. This chapter attempts to present the key research findings and suggests a number of avenues for further research.

These studies consisted of three parts, the first considered the effect of potassium on rice lodging under high N nutrition, using high rate of N (300 kg N/ha) with (200 kg K/ha) and without K, with combination of 50 mg P and 20 mg S/kg. The second part considered the inhibitory effect of salt stress in rice and the role of K in mitigating the salt-induced adverse effect on rice growth under varying salinity and K status. The third considered the effect of K on root parameters of rice under high N application and varying K rates. In the present study K effects on rice plants grown under saline conditions and on rice root parameters were studied under glasshouse conditions whilst other studies have been conducted under field conditions.

Under high N conditions, the study showed that K had significant effect on rice parameters, including tillers, height of plant, shoot and root dry matter production, stem diameter and stem strength. Also at K application at the rate of 200 kg K/ha, rice plants showed pronounced resistance to lodging incidence.

The importance of K application on the growth and yield of irrigated rice was observed in the present pot and field experiments. For soils, which are low in available K, addition of K could be beneficial. There is some evidence of the beneficial effects due to improved K nutrition. For example, the increase in plant K uptake following K application may be a consequence of improved plant growth, resulting from increased tillering and height of plants, thus carbohydrates increased with biomass of shoot, due to the key role of K in carbohydrate formation. As stated, K plays a key role in carbohydrate formation and sugar transfer.

The results suggest that increasing stem diameter in rice due to K application, could improve lodging resistance even in taller cultivars like Amber33. It was also observed that K had significant effect on stem strength, which is important in relation to stem stability against lodging (Chapter 3).

For this reason field experiments at three sites (Najaf, Al Diwaniyah and Ash Shamiyah) were conducted in Iraq. Results were similar to those obtained in the previous glasshouse experiments. Potassium positively affected the above parameters as well as the harvest index, number of panicle per m^2, 1000-grain weight, and grain and straw production.

Higher grain yield 5.9 and 5.8 t/ha was recorded in IR45427 and Amber33, respectively when K (200 kg/ha) was applied in Najaf location. Increased grain yield of examined cultivars depended mainly on increases in number of panicle per m^2, 1000-grain weight and probably to some extent on the number of filled grains in this study.

Grain yield (0.8 t/ha) of IR45427 and (2.37 t/ha) of Amber33 was low in the treatments that received (200 kg K/ha), at Al Diwaniyah location, in comparison with Najaf location which may have been related to high salinity and temperature as well as bird damage.

However, the present work provides further evidence that K plays an important role in mitigating the adverse effect of salinity through controlling the opening and closing of stomata under high salinity and temperature (Table 6.1 and Figure 6.3).

Additional evidence that rice well responds to K application was gained from the single replicate trial at Ash Shamiyah location. It appeared that K succeeded in overcoming lodging in the field.

In experiments (pot and field) reported here, K application in different level and methods were found to increase K concentrations in both soil and plant tissues. It also has significant effect on growth parameters of rice, increasing rice resistance to lodging and in mitigating the unfavourable effect of salinity. Evidence presented from the literature suggests these observed effects are due to improved enzyme activation, protein synthesis, photosynthesis, stomatal movement and water-relation (turgor regulation and osmotic adjustment) in plants and the synergistic effect between K and N.

Under saline conditions, the uptake of K and other major cations and the growth of plant could be affected. The K^+ concentrations of leaf and seedlings growth decreased with increasing salinity levels, while the Na^+ concentrations of leaf increased. High K supply is presumed to have a great effect to reduce the uptake of Na^+ and its harmful effects on plant growth parameters. The absence of K increased the mortality of rice plants by 37 – 60%.

As expected, salinity stress reduced photosynthesis and hence agronomic traits such as tillering and dry matter production were diminished. Application of K overcame these constraints to a significant extent.

The results of this experiment showed that the salinity caused a substantial loss in plant and in seedling establishment at salinity in the range of 6 to 8 dS/m as a result of extreme transport of the most common ions such as Na^+ and Cl^-. However, K application at rate 200 mg K/kg, reduced Na^+, lowered the Na^+ /K^+ ratio and raised K^+ resulting in increased salinity tolerance. Under these conditions, Ca^{2+} and Mg^{2+} concentrations in soil solution were also strongly enhanced by K application strategy (basal or/single). Also, K application significantly affected the AR^K. At salinity level of 3 – 4 dS/m, K reduced the adverse effect of salt stress and increased rice growth parameters (Chapter 4).

From these experiments, it could be concluded that growth of rice plants was reduced with increase in salt levels. However, K application at the rate of 200 mg K/kg was found to be effective in reducing the hazardous effect of salt (e.g. destroyed the cell membrane and restricted the growth and other metabolism processes) and in increasing growth parameters of rice plant. This indicates that the amount of K provided by fertiliser was enough for crop requirements, presumably due to the essential functions of K in cell osmoregulation, enzyme activation, cation-anion balance, stomatal function and the transport of assimilates thus, consequently increased tolerance to salinity. This was because most of applied K was not adsorbed by the soil and remained in water soluble forms.

In the root experiment, K had a significant effect of rice root parameters namely; RL, RSA, RV, RDM, RLD, RMD, RSR, RB and RD. These results reveal the important role of K in supporting a large root system which is very important for absorption of water and nutrients and for plant anchorage. The generally good root system was induced by the rate of K fertiliser 100 mg K/kg (as medium K level), however the rate of K 200 mg K/kg (as high K level) also significantly affected the root system but there was no difference between medium and high K level of this trait in this study. This suggests that for soils which are low in available K and for plants which have high K requirement this could be compensated by K application.

Apparently, the TRL and RLD, RSA and RSR were high following K-application in the surface soil depth of 0 – 5 cm. This positive effect is due to the fact that K enhances root growth and root penetration, which should result in better extraction of water and nutrients and in increase lodging resistance. By contrast, insufficient K results in accumulation of sugars in source organs due to an inhibitory to load phloem for basipetal transport processes (Romheld and Kirkby 2010).

The roots of rice grew quickly to 90 cm depth in all treatments, but with K application root parameters i.e., RLD, RSA, RV and root diameter (RD), increased at this depth. The root system increases play an important role in water and nutrient uptake from deep soil layers and in increased anchorage for the plants and resistance against root lodging.

As plant growth was increased by application of K, extra carbon assimilated was transferred to roots, resulting in improved root growth. Therefore, a large root system, with deep and extensive distribution, is able to establish a solid foundation for plants.

Application of K fertiliser significantly improved root system growth and evidence from this thesis suggests that increased overall production may play a more significant role in alleviating K deficiency and lodging than previously thought. Further research under field conditions is required to determine the contribution of improved root growth to yield increases following K application to rice.

7.1.2 Further studies

It is recommended that research into the production of rice under flooded conditions be continued, with particular emphasis on issues such as K application. The following three complementary approaches may also address the issues associated with lodging of rice in Iraq.

Firstly, it is necessary to evaluate soil fertility management practice of rice farmers in Iraq. Increasing crop quality and overall performance requires a complete and balanced soil fertility program that supplies not only needed high N rate (~300 kg N/ha) but also P and K, as well as secondary nutrients based on soil tests. It is necessary to provide the essential nutrients (NPK) in the proper balance (e.g. decreased N application, in combination with P and K), helping to ensure that nutrition is not a limiting factor in achieving top performance.

As the duration of the rice crop is increased, the plant nutrients and water required are increased. Nutrient balances and trends in soil fertility also tend to differ widely in the various intensive cropping systems for example rice-wheat sequences in Iraq. Short-duration cultivar is shorter than other cultivar (i.e. Amber33) by about 50 days. It comes to harvest in 105 – 110 days. Amber33 consumes a large amount of water since it stays about 155 days in the field; also the supply of nutrients in the soil is exhausted. The response of short duration cultivars to NPK nutrients should be investigated to substitute long duration cultivar by short duration cultivar, for saving a portion of irrigation water without reduction in rice areas. Also due to the genetic control of the aroma trait, this trait can be converted from aromatic rice cultivars such as Amber33 (long duration cultivar) to a short duration rice cultivar

One further suggestion is to investigate effect of silicon (Si) on lodging as Si is important for the healthy growth of rice (Epstein 1994) and for stability of rice production' in combination with NPK on the growth and lodging resistance of rice plant and its role in reduction Na uptake into the shoot under saline conditions. This could be achieved by the use of a glasshouse where the environment can be better controlled, thus would need to be repeated on a large scale under field conditions.

Potassium silicate (K_2SiO_3) is a source of highly soluble Si (Epstein 1994; Muriithi *et al*. 2010). Applications of K_2SiO_3 are primarily intended to provide supplemental silica (SiO_2). Most soils contain significant quantities of silica, but continuous cropping, particularly with crops such as rice that accumulate significant quantities of silica, can reduce plant available levels of Si to the point that supplemental Si fertilisation is required. High silica uptake has important role in improving lodging resistance. Under saline conditions, potassium silicate may be given instead of potassium chloride (KCl). We can also apply potassium sulphate (K_2SO_4) along with Si as foliar or/and root applications.

7.2 Conclusions and recommendations

7.2.1 Conclusion

On the basis of results presented in this thesis, it can be concluded;

Potassium application improves plant growth, tissue K concentrations and grain yield, stimulates and increases root growth, and may overcome lodging in rice under flooded saline conditions.

7.2.2 Recommendation

Better fertiliser management is essential to both match N application rates to yield potential and plant requirements (avoiding over-fertilisation with N) and to apply K where lodging incidence significantly decreases plant yield. Extension programs to this effect should be instituted to improve N and K fertiliser use efficiency.

Authorities should encourage farming system modification to increase the retention of straw to increase soil organic matter concentrations (and eventually soil organic N) and more importantly, allow for leaching of tissue K into the surface of fields in which rice has been grown to ultimately decrease reliance on inorganic N and K inputs to sustain yields.

The strong preference of Iraqi rice producers for Amber33 suggests only two pathways for managing lodging resistance: 1) increased application of K fertiliser in areas where K responses drive lodging incidence; 2) a breeding program to decrease plant stature and cultivar growing length. The first pathway is short-term and is likely to be successful in increasing rice yield, the second requires much longer term vision.

A third alternative is to identify the unique aromatic traits that render Amber33 such a popular cultivar of rice and breed those traits into existing short stature and shorter growing period cultivars. Short stature cultivars have greater lodging resistance and shorter growing season requirements. As water resources in Iraq are limited and climate change-induced droughts have plagued the area since 2006, shorter, more water-efficient cultivars are essential for rice food security.

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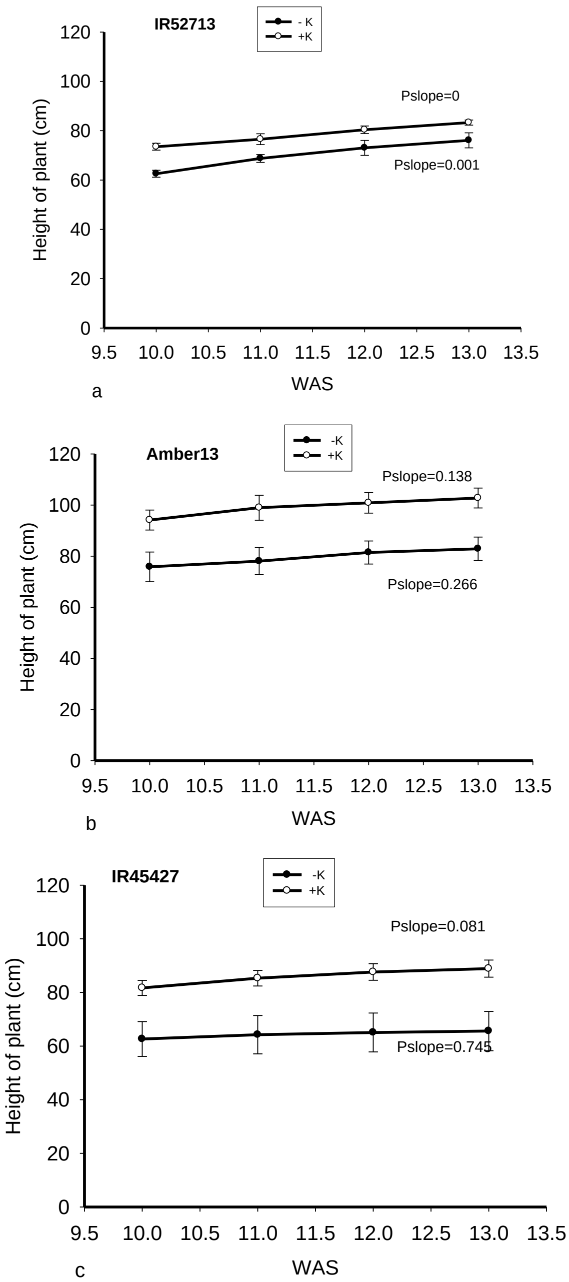
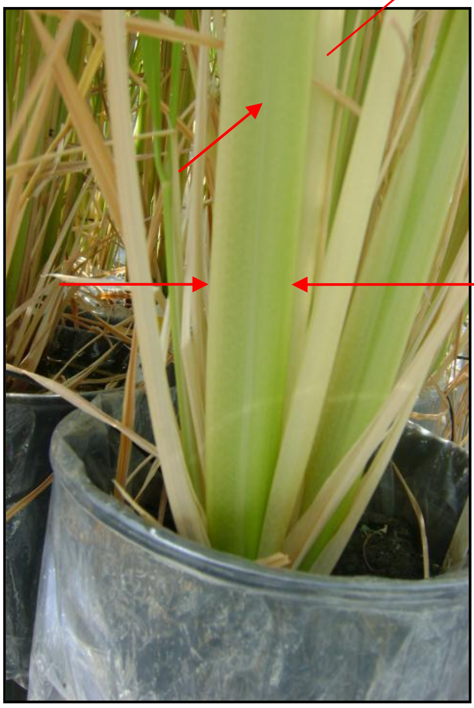
APPENDICES

Appendix 3.1 Effect of K application (no potassium vs 200 mg K/kg) on plant height (cm) of three rice (*Oryza sativa*) cultivars grown for 10 – 13 weeks in a glasshouse on a K responsive Black Vertosol. Error bars refer to ± SEM of 4 replicates.

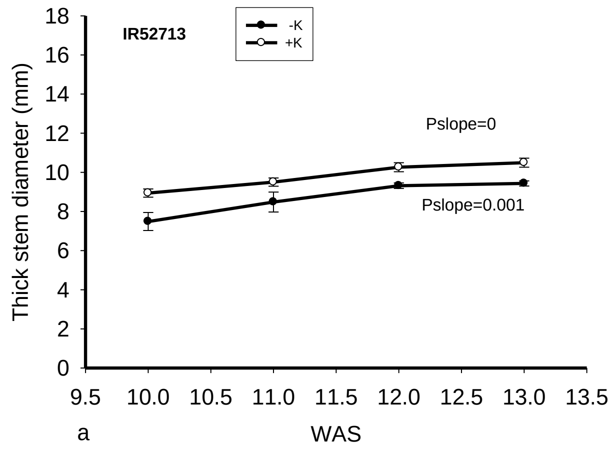
Plotted over time, the slope of plant height changes did not differ significantly ($P \geq 0.081$) between weeks 10 – 13. However, some cultivars differ in their change in plant height. In particular, a significant (Pslope=0 and Pslope=0.001) increase happened overtime between weeks 10 to 13 in IR52713 cultivar.

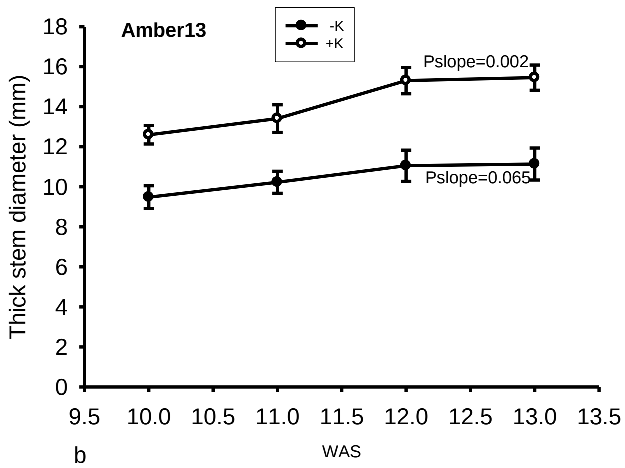


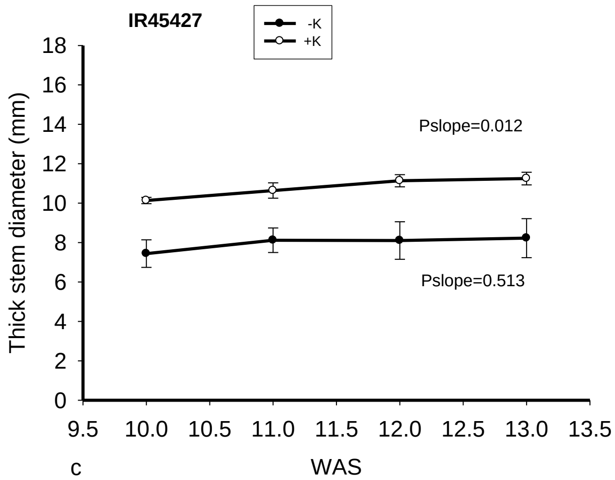
Appendix 3.2 Thick and thin stem diameter in Amber33



Appendix 3.3 Effect of K application (no potassium vs 200 mg K/kg) on thick stem diameter (mm) of three rice (*Oryza sativa*) cultivars grown for 10 – 13 weeks in a glasshouse on a K responsive Black Vertosol. Error bars refer to ± SEM of 4 replicates.

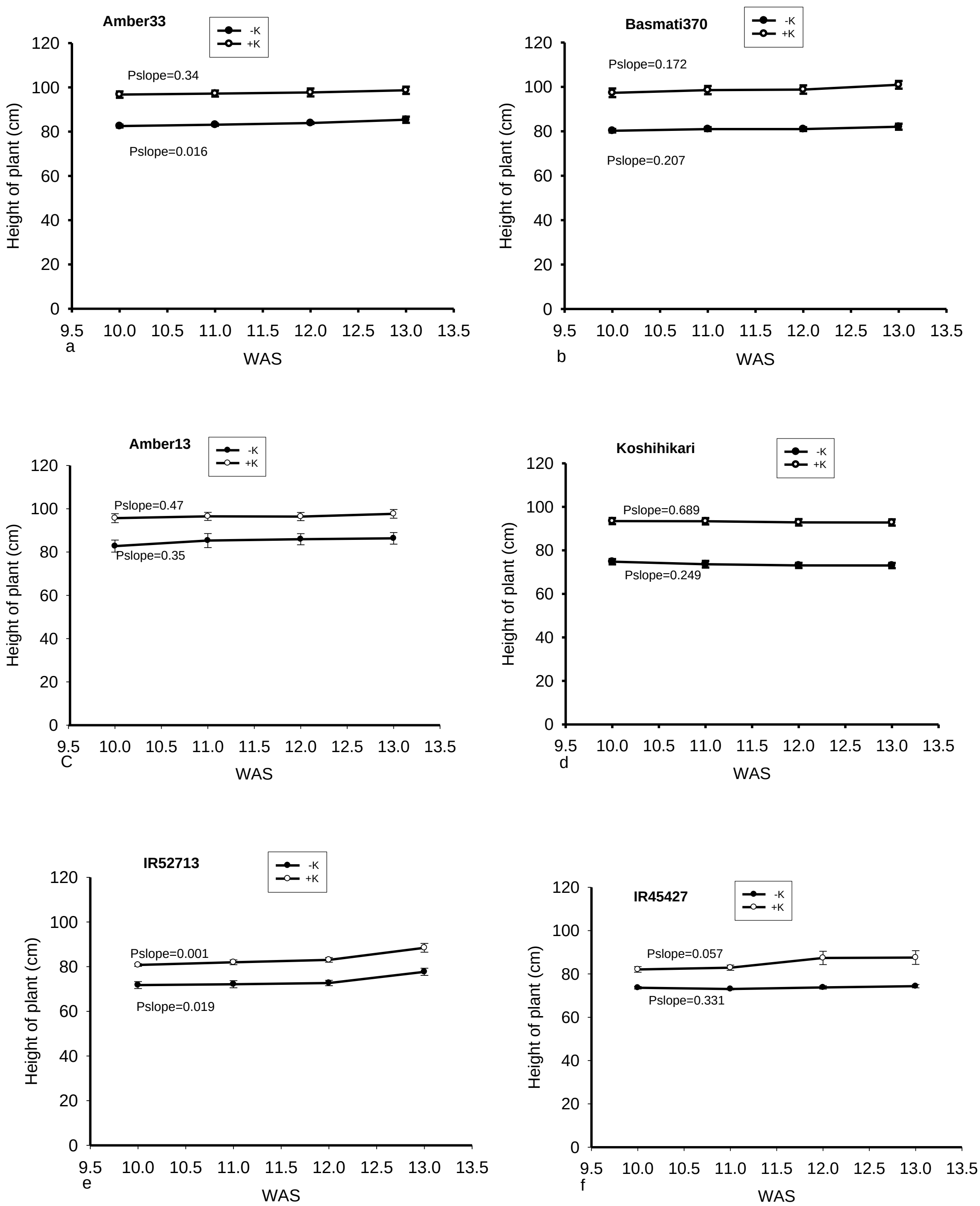




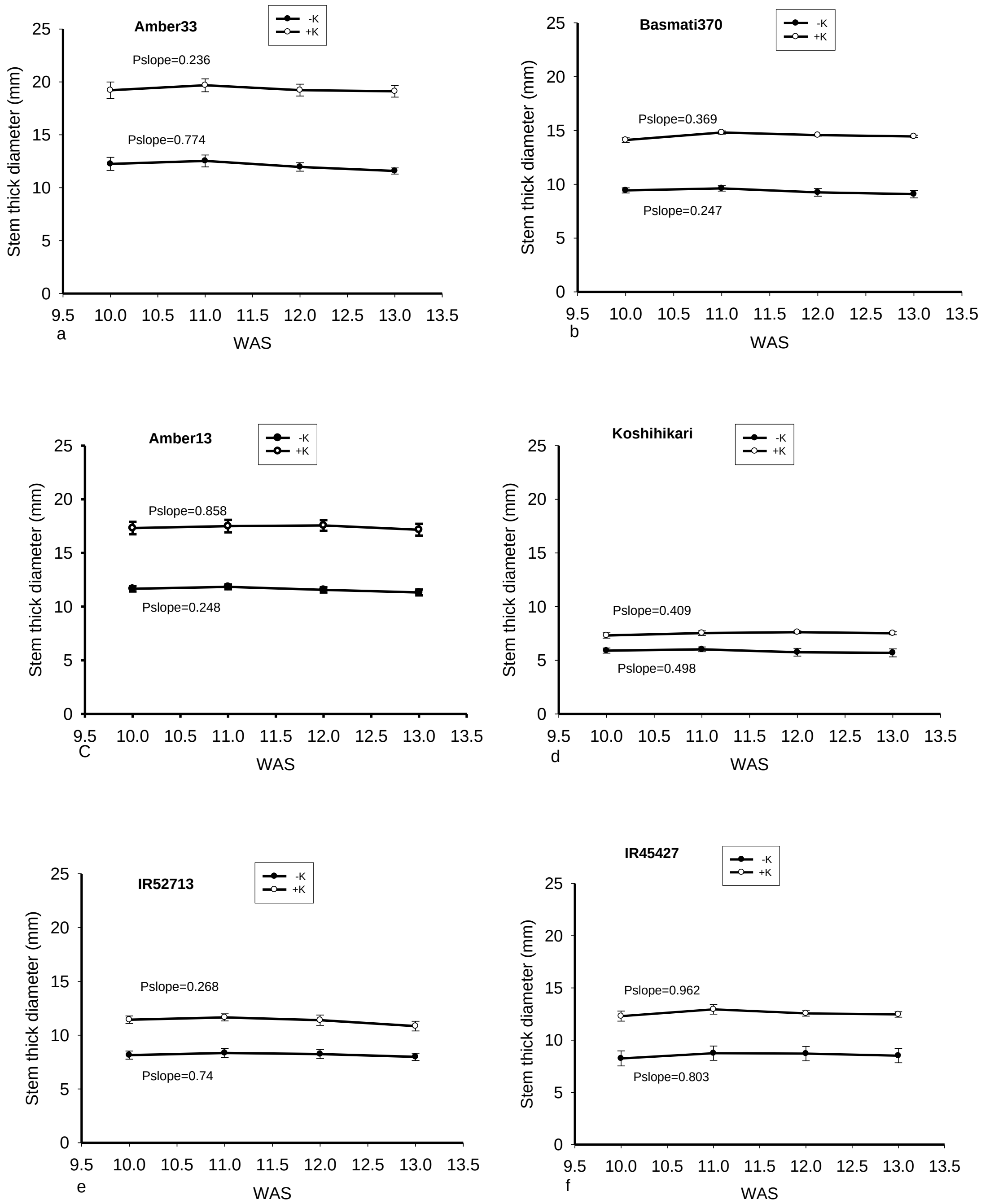


Appendix 3.4 Effect of K application (no potassium vs 200 mg K/kg) on plant height (cm) of six rice (*Oryza sativa*) cultivars grown for 10 – 13 weeks in a glasshouse on a K responsive Black Vertosol. Error bars refer to ± SEM of 4 replicates.

In particular, in IR52713 cultivar, in term of plant height, there were no cultivar-by-K interactions (P > 0.05) during the winter experiment, which were observed during the summer trial (P = 0.007).



Appendix 3.5 Effect of K application (no potassium vs 200 mg K/kg) on stem thick diameter (mm) of six rice (*Oryza sativa*) cultivars grown for 10 – 13 weeks in a glasshouse on a K responsive Black Vertosol. Error bars refer to ± SEM of 4 replicates.



Appendix 3.6 Effect of cultivar and interaction (cultivars X K) on tissue K concentration (%), tiller number, plant height (cm), stem diameter (mm), SDW and RDW (g) and stem strength (g).

Winter experiment

Variables	Source	
	Cultivar (C)	C X K
K-leaves	ns	**
K-stem	***	***
K-root	***	*
tillering	***	ns
Height	***	**
Thick stem diameter	***	***
Thin stem diameter	***	*
SDW	***	*
RDW	***	***
Lower stem strength	***	**
Upper stem strength	**	. (0.08)

Summer experiment

Variables	Source	
	Cultivar (C)	C X K
K-leaves	*	ns
K-stem	*	ns
K-root	***	*
tillering	***	**
Height	**	ns
Thick stem diameter	***	ns
Thin stem diameter	. (0.06)	ns
SDW	***	ns
RDW	***	**
Lower stem strength	***	ns
Upper stem strength	***	*