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The effects of sodicity on the growth and yield of wheat

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A thesis submitted to the University of Wales, Bangor

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Abstract

The effects of sodicity on seedling emergence, ion uptake, growth, survival and yield of hexaploid wheat varieties and tetraploid wheat genotypes were investigated. For this study a series of pot experiments was conducted under glasshouse and growth room conditions at the Henfaes Agriculture Research Station, University of Wales, Bangor, UK. Sodicity was artificially created by treating soils with $NaHCO_3$. The relative effects of poor soil structure and high ESP were investigated by treating soil with $NaHCO_3$ and by stabilising soil aggregates with an anionic polyacrylamide (PAM) soil conditioner. Comparison of the effects of salinity and sodicity was investigated by adding a mixture of NaCl, $CaCl_2$ and $MgCl_2$ salts into the soil. The effects of sodicity at different growth stages were investigated in experiments with seedlings and mature plants and in experiments conducted by transplanting wheat seedlings into sodic soil.

The results of this study revealed that, with the exception of seedling emergence, the adverse effects of sodicity were higher than those of salinity. The effects of sodicity increased with increase in exchangeable sodium percentage (ESP) of the soil, and were generally more pronounced in clay loam and loamy sand soils with low organic matter and N %. The adverse effects of salinity were associated with high Na^+ and Cl^-, low K^+/Na^+ ratio in leaf sap and osmotic effects, possibly reflected by high EC_e. The adverse effects of sodicity were associated with high Na^+, low K^+, Ca^{2+} and lower K^+/Na^+ ratio in leaf sap, grain and straw dry matter, but not with decreased concentrations or toxic levels of micronutrients. The large effects of sodicity were related directly with high ESP and pH and indirectly with poor soil structure (low water stable aggregates %).

Addition of PAM to sodic soils resulted in large increases in the water stable aggregates (WSA %), which in turn increased seedling emergence %, survival %, shoot height, shoot dry weight, grain yield and almost all yield components in sodic soils. Addition of PAM also increased K^+ and K^+/Na^+ ratio and decreased Na^+ in leaf sap, grains and straw dry matter.

Wheat plants transplanted into sodic soil survived and produced ears, but the surviving plants did not produce grains at high ESP. Transplantation of 16 and 21 day old seedlings generally resulted in higher grain and straw yield than the sowing of dry and pre-germinated seeds in sodic soils with ESP below 40. The improved performance of transplanted seedlings in sodic soils was not clearly associated with changes in ion concentrations in flag leaf sap.

There were differences between wheat varieties and genotypes in terms of how they were affected by sodicity, and how they performed in sodic soil treated with PAM. Kharchia-65, a hexaploid wheat variety, and $R112^+$ and $R173^+$, tetraploid wheat genotypes which posses a gene (Kna1) which enables them to discriminate between K^+ and Na^+, were generally tolerant to both sodicity as well as salinity from seedling stage to maturity. The improved growth and yield of most of the varieties and genotypes in the PAM treated sodic soils was generally associated with lower leaf Na^+ and higher K^+ and K^+/Na^+ ratio, but not with increased concentrations of micronutrients.

These results suggest that substantial improvement in the performance of wheat in sodic soils can be quickly achieved by adding PAM. These results also indicate that the primary cause of low wheat yield in sodic soils with ESP up to 40 or 50 may be poor soil structure and that the decrease in yield due to ion toxicity is relatively small. In sodic soils with ESP above this range 40 to 50 the major cause of low yield may be high exchangeable Na^+ and the effect of improved structure is relatively smaller. The results from this study support the use of PAM in sodic soils and selection of varieties such as Kharchia-65 and genotypes $R112^+$ and $R73^+$ for use in future breeding programmes to screen out new local genotypes that can tolerate poor soil structure as well as salts.

To my respectable teacher Professor Dr Nabi Bux Sial

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Abbreviations

%	per cent
/	per
°C	degree Celsius
R^- (superscripts)	Recombinant without Kna1 gene
R^+ (superscripts)	Recombinant with Kna1 gene
@	at the rate of
Anova	analysis of variance
Bakh.	Bakhtwar
DAS	days after sowing
DAT	days after transplanting
df	degrees of freedom
DM	Dry matter
DS	dry seed
EC_e	electrical conductivity of the saturation extract
EMS	error mean square
ESP	exchangeable sodium percentage
ESR	exchangeable sodium ratio
H. I.	harvest index
Hr	hours
Khar-65	Kharchia-65
Kna1	K^+/Na^+ discriminating gene
L. S. D.	least significant difference
No. or no.	number

N. S.	not significant
p	plant
PAM	anionic polyacrylamide (Soil conditioner)
PG	pre-germinated seed
pH (1:2.5 H_2O)	soil pH measured in water using 1:2.5 soil water extract
ppm	parts per million
R. H.	relative humidity
S. E. D.	standard error for the differences between means
SAR	sodium adsorption ratio
Trt.	treatment
Var* sodicity	variety interaction sodicity
WSA %	water stable aggregates percentage
Wt	weight

CHAPTER 1

General introduction

CHAPTER 1

General introduction

The loss of crop production from salt-affected soils is a serious and world wide problem (Brown, 1981; Gupta and Sharma, 1990; Abbas *et al.*, 1994). Where these problems occur the crop yield decreases and in some parts of the world several thousands hectares of land have been lost from agricultural use (IIMI, 1998). This situation is getting even worse in arid and semi-arid regions, especially in the countries where irrigation is the main source of water for crop production (IIMI, 1998).

Salt-affected soils can occur naturally due to the original or direct nature of the parent material (USSL Staff, 1954) or indirectly due to the chemical weathering of primary minerals e.g. chloride bearing minerals such as biotite and hornblende and sodium, potassium and calcium bearing minerals such as feldspars (Gunn, 1986). The other sources like accession of cyclic salts in coastal regions, addition of dissolved salts to rain by aeolin processes (Elliot and Holman, 1986) and formation of HCO_3^- as a result of the solution of atmospheric or biological CO_2 in H_2O, have also been considered as important sources. All irrigation waters (Rowell, 1994) including good quality water contain some dissolved salts. During their application into fields they can trigger secondary salinisation. Another possibility for the formation of these soils is the saline or sodic ground water, which is rising up due to impeded drainage. In some countries of the world, irrational use of irrigation water is the most common practice. Addition of excess water brings the water table level (including dissolved salts) closer to the soil surface, where high temperature makes the water together with the dissolved salts rise up through capillary movement. During the capillary movement some salts (less soluble salts) may precipitate in any layer of the soil profile to form gypsic, calcic, salic and natric horizons, but in hot and dry climates, especially in arid and semi-arid regions, the loss of water through high evaporation facilitates the accumulation of salts on the soil surface forming a white crust (efflorescence) of salts (Sial, 1985). In coastal regions flooding by sea water also brings the salt into the neighbouring sites. Hence in coastal regions including parts of eastern England, Belgium, Netherlands (Rowell, 1994), the delta area of river Indus and the coast at Thatta, Badin Sindh, Pakistan and the Bengal coast of India have been salinised by sea water flooding.

Due to the evaporation or utilisation of water by plants, the concentration of the soil solution increases. Hence the precipitation of $CaSO_4$, $CaCO_3$ and $MgCO_3$ occurs. This increases the concentration of free sodium ions in soil solution, some of which can replace the Ca^{2+} and Mg^{2+} ions on the exchange complexes. This situation (sodication) occurs when at least half of the soil solution is dominated by Na^+, otherwise the Ca^{2+} and Mg^{2+} cations are strong and possibly cannot be replaced by Na^+ easily.

Due to their difference in morphology, physical and chemical behaviour, salt affected soils have been separated into three groups: saline, saline-sodic and nonsaline-sodic soils.

The term saline refers to the presence of an excessive amount of soluble salts, hence the EC_e (electrical conductivity of the saturation extract) of saline soils is more than 4 dSm^{-1} at 25 ^0C, pH is less than 8.5 and the exchangeable sodium percentage (ESP) of these soils is less than 15. Mostly these soils show a white puff of salts on their surface hence Hillgard (1906) called them *''white alkali''* soils and Russian soil scientists refer to them as ''*Solonchacks*''(USSL Staff, 1954). Soil salinity can occur in both developed or undeveloped soil profiles. The concentration of Na^+ in the soil solution mostly remains lower than that of other cations (Ca^{2+} and Mg^{2+}). Hence the chances for Na^+ adsorption on exchange complexes are very few, compared to the adsorption of other cations. The most common anions present in these soils are Cl^-, SO_4^{2-} and some times NO_3^-. There is very little chance of HCO_3^- occurring although it may be present in small amounts in these soils. If drainage is not a problem these soils can easily be reclaimed by a leaching process, without employing any chemical amendment.

Sodic soils are quite different from saline soils. The EC_e of these soils is less than 4 dSm^{-1} (saturation extract), the pH of these soils mostly ranges from 8.5 to 10 and the ESP is above 15. However, in the absence of high lime content the availability of H^+ ions may not allow sodic soils to develop a pH higher than 6, especially in the surface layers, although, they still can show an ESP of greater than 15. Such sodic soils are called ''*degraded sodic soils*'' (De-Sigmond, 1938 as reported in USSL Staff; 1954). Sodic soils are most commonly formed due to the leaching and removal of soluble salts from the soil profile. Leaching of soluble salts leaves behind a higher concentration of sodium ions so that Na^+ finally becomes a predominant adsorbed cation on the exchange complexes. Due to the presence of $NaHCO_3$, and high pH, the deflocculating effect of Na^+ is increased. This also facilitates the dissolution and dispersion of organic matter (Carr and Greenland, 1975). Because of the evaporation the dispersed and dissolved organic matter comes up and deposits on the soil surface. This darkens the colour of the soil and the soil structure becomes weaker. Hence Hillgard (1906) named these soils as ''black alkali'' soils, while the Russian scientists called them ''solonetz'' (USSL Staff, 1954). The dispersion of clay can also occur at ESP as low as 2 (Waller and Wallender, 1993). Hence in some countries, like Australia, sodicity is considered as a soil with an ESP of greater than 6 (Naidu and Rengasamy, 1993). However, in almost all other countries the threshold level of ESP is 15.

The soil solution of sodic soils contains a relatively low concentration of soluble salts, but the composition is considerably different from that of normal and saline soils. Sodicity is mainly due to higher concentrations of CO_3^{2-} and HCO_3^- ions, but in some cases sodic soils may not show an appreciable amount of CO_3^- ions. This indicates that in most sodic soils the sodicity occurs because of HCO_3^- ions (IIMI, 1998). The presence of CO_3^{2-} or HCO_3^- ions introduced by different sources (irrigation or groundwater) causes an increase in pH (Charters, 1993; Rowell, 1994) that also results in the precipitation of Ca^{2+} and Mg^{2+} ions as $CaCO_3$ and $MgCO_3$. Hence the soil solution of sodic soils usually contains a low concentration of Ca^{2+} and Mg^{2+} cations, Na^+ being the dominant one.

Saline-sodic soils show higher EC_e (>4 dSm^{-1}) and higher ESP (>15). With the downward movement of soluble salts through leaching these soils can show high pH (>8.5) and de-flocculation of clay otherwise in the presence of high EC_e they may not show high pH and de-flocculation of clay. The lower concentration of soluble salts after leaching from the surface layers can also provide a chance for sodium to be hydrolysed into NaOH, that may react with atmospheric CO_2 to form Na_2CO_3 salt. Prior to chemical treatments (with gypsum or sulfur) the reclamation of saline-sodic soils with irrigation water always results in sodicity problem. Also after a certain period of time saline-sodic soils can show morphology similar to pure sodic soils, because the highly dispersed sodium rich clay moves down to be accumulated in lower layers, leaving behind the coarse soil particles in a few inches at the soil surface.

Soil sodicity is characterised by the presence of excessive amounts of exchangeable sodium on the exchange complexes, which is detrimental to both soils and plants (Allison, 1952; Sharma, 1991; Cook and Warren, 1997). Sodic soils mostly have dense, blocky, single grain, poor soil structure (USSL Staff, 1954). They are hard to till when dry, especially sodium rich clayey soils (Rowell, 1994), and have low hydraulic conductivity when wet. Because of their adverse physical (poor soil structure, impeded drainage) and chemical (excess exchangeable sodium and high pH) properties sodic soils need special attention for amelioration and cultivation. To reclaim sodic soils for crop cultivation, the high values of pH and ESP need to be reduced and the soil structure needs to be improved (Carr and Greenland, 1975). The reduction of pH and displacement of sodium using chemicals (sulfer or gypsum) and improvement of soil structure are usually lengthy processes. Chemical treatments can only be effective in replacing the Na^+ from the surface, but not from the subsoil and it may take 2-3 years to improve soil structure. Thus, we need to find an alternate, artificial method that can rapidly restore good soil structure to dispersed soil (Allison, 1952).

Studies on the effects of soil sodicity have been done in many crops. These include rice (Murty and Janardhan, 1971), barley (Choudhary *et al.*, 1996), oilseed rape (Boem and Lavado, 1996), groundnut (Singh and Abrol, 1985), sorghum, corn, safflower, ryegrass and tomatoes (Bains and Fireman, 1964), and to some extent wheat (Mehotra and DAS, 1973; Joshi, 1976, 1982; Chhipa and Lal, 1991; Choudhary *et al.,* 1996). Although the effects of sodicity on agricultural crops have been extensively studied, relatively little is known about the separate physical and chemical effects of sodic soils on plants. More than 40 years ago some workers (Allison, 1952; Martin and Jones, 1954; Bernstein and Pearson, 1956; Allison and Moore, 1956; Pearson and Bernstein, 1958) tried to grow plants in sodic soils, avoiding the effects of poor soil structure by using synthetic organic type soil conditioners. Later, Carr and Greenland (1975) attempted the same study using synthetic polymers as stabilising agents. However, due to the cost and unavailability of suitable soil conditioners their use has not been incorporated into commercial agricultural practices on a large scale. Also, at that time, the effects of toxic salts on plants and the mechanisms of salt tolerance were not well understood. Hence there have been few attempts at quantifying the physical and chemical effects of sodic soils on the physiology, growth and yield of plants.

Although the effects of polymers on plants in the presence of high exchangeable sodium have not been described with any degree of certainty, almost all reports, including some recent evidence (Saleh and Letey, 1990) suggest that polymers can be used as aggregate stabilising agents in the presence of high exchangeable sodium. In

1954 an important clue, based on the studies of Allison (1952) and Martin *et al.* (1952), was published in Hand book 60 (USSL Staff, 1954) stating that:

> *''although it is not economically feasible for general agricultural use, polymers can be used as an effective tool in research. By their use, for instance, plant response to different ESP levels can be studied on conditioned soils in the absence of poor soil structure and accompanying conditions of deficient aeration and low water movement in alkali soils''.*

Compared to that period the possibility of stabilising aggregates with synthetic polymers has now been recognised, and several companies (*Allied Colloids Agricultural Division* and *JRM chemical* etc.) have developed commercially available products (*SOILTEX G1, SOILTEX L1* and *SoilMoist* etc.). These products have mainly been developed for use on soils growing high value vegetable crops, where good and uniform crop establishment is important in ensuring plant uniformity at harvest. Techniques for measuring ion uptake are now well established and plant scientists are familiar with effects of toxic ions on growth and yield. In addition, traits that are associated with the salt-tolerance have also been identified. The opportunity therefore exists to follow the clue published by USSL Staff in 1954, conducting research to separate the physical and chemical effects of sodic soils on crops using these new synthetic polymers. Information from such studies may be useful for agronomist and growers, seeking to improve sodic soils and the yields of crops grown on them. It may also be useful for plant breeders, developing varieties that are resistant to both poor soil structure and high salt concentrations.

Pakistan lies in the arid and semi-arid climatic regions. High average mean summer temperature (40 °C); low rainfall (only occurring in August and September); high rates of evapotranspiration; shallow water table level; seepage from unlined canals, distributories and water-courses; pumping of saline and sodic groundwater into crop fields and absence of an effective drainage system have resulted in the increase in salt-affected area. Thus salt affected soils are a major problem in Pakistan. Approximately 4.79 m ha of the country's irrigated land is salt affected (Muhammad and Ghafoor, 1983), out of which 1.89 m ha is saline, 3.74 m ha is saline-sodic and 0.028 m ha is sodic in nature.

Locally in Sindh province the problem of salt-affected and waterlogged soils continues to increase, especially in some districts like Naushahro Feroze, Khairpur Mirs, Larkana, Mirpur Khas, Hyderabad and Thatta. Almost 50% of the citrus and mango gardens are out of production, and the provincial government in these areas has imposed a ban on cultivating the rice crop, except in Larkana district (rice tract). Most of the people have migrated from villages (in the area surrounding of Phull, Kandiaro Thari-Mirwah, Padidan and Pir sadique) facing these problems. In addition, there are no natural grazing pastures any more for dependent animals particularly camels, sheep and goats etc. Many tenant farmers have now abandoned their farms in the worst affected areas of the country. As a result of this the former landlords must farm their own land themselves. Although, the number of people affected by salt-affected and waterlogged soils in Pakistan is not known, rough estimation presented by Qureshi and Lennard, (1998) shows that about 16 million people are presently directly affected and this number will also double by the year 2020.

Wheat is a major food crop in Pakistan. It is growing on about 3.36 million ha land. Out of 19 million tonnes of wheat production recorded in 1997-98, the Punjab province produced about 14 million, Sindh produced 2.6 million, NWFP 1.3 million, Baluchistan produced 1 million and AJ & K produced 0.1 million tonnes of wheat (Daily Dawn Feb,11th 1999). However, the country's annual wheat production does not meet the demand, because about 3 times a day each person consumes a considerable number of breads, locally called chapatti, made from wheat flour. Even in very poor families who cannot afford meat and commercial vegetables, they just only eat chapatti with milk at dinner, curd or yoghurt at breakfast and some wild vegetables at lunch time. To fulfil this requirement every year Pakistan spends considerable amounts of money ($710 million to import 4.1 million tons during 1997-98) (Daily Dawn. Feb. 11th 1999) to import wheat from other countries like USA, Australia, Canada etc. Wheat straw also has a great market value in Pakistan, especially where there is a shortage of fodder grasses and it is used as a substitute of green fodder crops. Poor communities also mix the wheat straw in mud to make mud plaster for their huts and houses. One of the main reasons for low wheat production in Pakistan is the low per ha crop yield, which in many areas is due to the effects of waterlogged and salt affected soils, particularly saline and sodic soils. To decrease wheat imports and to make the country more self sufficient in wheat production, we need to put some more effort into cultivating these salt affected and waterlogged lands which are lying barren or under water.

The work reported in this thesis aimed to investigate the separate physical and chemical effects of sodicity on wheat, using polymers (soil conditioners). Wheat was selected for study as it is one of the major cereal crops, well adapted to the arid and semi-arid regions and is among the moderately salt-resistant crop species (Mass, 1986). In addition to sodicity studies, some experiments were conducted to compare the effects of salinity and sodicity. Plants differ greatly in their capacity to tolerate salts, which also depends on variety or species (Sharma, 1991), and their growth stages (USSL Staff, 1954). To test this hypothesis a number of hexaploid wheat varieties and some durum wheat genotypes were compared at different growth stages viz. from seedling emergence to yield. To avoid the stress of salt affected soils at early growth stages, in some experiments seedlings were initially raised in a nursery before transplanting into soil filled pots. Soil sensitivity to ESP varies across soil types (Cook and Warren, 1997) and hence to compare the effects of high ESP on different soils, soils with different textures were used.

The overall objectives of the work reported in this thesis were: to try to quantify the separate effects of toxic ions and poor structure of sodic soils on wheat, to study the effects of sodicity on wheat at different stages of growth and to compare the effects of salinity with sodicity.

CHAPTER 2

Review of literature

CHAPTER 2

Review of literature

2.1 Global distribution of salt-affected soils

Although there have been several reports showing the extent of salt-affected soils in the world, it is not always clear in these reports as to whether the authors are referring to salt-affected soils in general, or saline and sodic soils in particular. Hence it is hard to separate the estimations of sodic from saline soils. Although there have been no precise measurements of the extent of salinity on a global scale, the best estimates (Table 2) indicate that large areas in the major countries are already badly affected by sodicity and salinity.

Table 2. Global distribution of salt-affected soils (Sumner and Naidu, 1998)

	Area in millions of ha		
Continent	Saline	Sodic (Alkali)	Total
North America	6.2	9.6	15.8
Central America	2.0	--	2.0
South America	69.4	59.6	129.0
Africa	53.5	27.0	80.5
South Asia	83.3	1.8	85.1
North & Central Asia	91.6	120.1	211.7
Southeast Asia	20.0	--	20.0
Australia	17.4	340.0	357.0
Europe	7.8	22.9	30.7
Total	351.5	581.0	932.2

Present estimates given by various workers for India range from 7 to 16 million ha, or from 27 to 60% of the irrigated land. Estimates of the percentage of irrigated land that is salt affected for other countries are as follows: Pakistan 14% (which is also increasing at about 0.2 to 0.4 per cent per annum (Ishaque, 1982), Israel 13%, Australia 20%, China 15%, Iraq 50%, and Egypt 30 % of their irrigated land (Ghassemi *et al.*, 1995).

2.1.1 Extent of sodicity

Although there have been very few reports on the extent of sodic soils in the world, in terms of the total area of salt-affected soils, sodic soils occupy the largest proportion (Table 2). In relation to total surface area of any continent in the world, Australia has the largest salt affected area (Table 2) and has over 28% of the total land affected by sodicity (Naidu, 1992). The second largest proportion of the land occupied by sodicity is in the former USSR (Table 2.1). Several countries are facing this problem (Table 2.1). The Indian sub continent is also affected by sodicity problems. Nearly 25 % of the estimated 12 million ha of saline/sodic soils in India, are lying barren mainly due to high sodicity (Yadave and Gupta, 1984). Out of this about 2 million ha land affected by sodicity is in the coastal regions of Bengal, Orissa, A. P. Kerata, Meharastra and Gujrat (Murthy and Janardhan, 1971).

Due to different criteria of survey there are large differences between the estimates of sodic soils reported by different agencies in Pakistan. As it is already mentioned in Chapter 1, out of 4.79 million ha salt affected area in Pakistan, 0.028 million ha is sodic in nature. Sodic soils are mainly located in Sindh province (Muhammad and Ghafoor, 1983), because the alluvial parent material of the Indus plain, transported by rivers, contains Na_2SO_4 and NaCl salts, which are responsible for sodication (Sial, 1985).

2.1.2 Economic impact of salt-affected soils

The economic impact of salt-affected soil has not been calculated with any degree of precision, but there is some evidence that the yields of rice and wheat can be decreased on degraded soils by up to 50% compared to the unaffected land. Other estimates have shown that the net income of farmers on salt-affected land can be up to 90% lower than that of farmers on unaffected land. A more thorough analysis by Joshi and Jha, (1991) showed that the gross income of farmers on salt-affected soil was 72% lower than that of farmers on unaffected soil.

Table 2.1. World distribution of sodic soils (Lubbock, 1977 as reported in Sumner and Naidu, 1998)

Continent	Country	Area of sodic soils '000ha
North America	Canada	6974
	United States	2590
South America	Argentina	53139
	Bolivia	716
	Brazil	362
	Chile	3642
Africa	Algeria	129
	Angola	86
	Botswana	670
	Cameroon	671
	Chad	5950
	Ethiopia	425
	Ghana	118
	Kenya	448
	Liberia	44
	Madagascar	1287
	Namibia	1751
	Niger	1389
	Nigeria	5837
	Somalia	4033
	Sudan	2736
	Tanzania	583
	Zambia	863
	Zimbabwe	26
South Asia	Bangladesh	538
	India	574
	Iran	686
North and central Asia	China	437
	USSR (Former)	119628
Australasia	Australia	339971

Ghassemi *et al.* (1995) quoted some estimates of damage to the economy of a few countries facing the problem of salt-affected land. For Pakistan, they give the cost of damage as US$300 million per year for Punjab and North West Frontier Province (NWFP) alone, based on estimates of the Water and Power Development Authority of Pakistan (WAPDA). In Australia, it has been estimated that annual agricultural loss from salt-affected land in the Murray-Darling Basin amounts to more than US$200 million, and for the Colorado River Basin in California, the estimate is as high as US$750 million per year (Ghassemi *et al.*, 1995).

This literature review is mainly concerned with the effects of sodicity on plants. It is recognised that sodicity also has effects on soils, but they are not extensively reviewed here. For back ground information on this the reader is referred to texts by USSL Staff (1954); Brady (1990); Rowell (1994) and Sumner and Naidu (1998).

Although, the emphasis of the review is on the effects of sodicity, as the research reported in this thesis includes some comparisons between salinity and sodicity, the effects of salinity are also mentioned.

2.2 Plants under saline and sodic conditions

2.2.1 Germination and seedling emergence

As is clearly mentioned by Bewley and Black (1994), in the scientific literature the term germination is often used loosely and sometimes incorrectly, and so it is important to clarify its meaning. Germination begins with water uptake by the seed (imbibition) and ends with the start of elongation by the embryonic axis, usually the radicle. Germination does not include seedling growth, which commences when germination finishes. Hence it is incorrect, for example, to equate germination with seedling emergence from soil, since germination will have ended sometime before the seedling is visible. Similarly, some of the reports showing the effects of salinity are not very clear, in that they have not differentiated between effects on germination and seedling emergence.

2.2.1.1 Seedling emergence under saline conditions

Salinity decreases the germination and emergence of crops, including barley (Bishnoi and Pancholy, 1980; Kabar, 1986; Abou-Sharar, 1988; De-Ming *et al.*, 1995);

alfalfa (Uhvitus, 1946) and wheat (Larik and Hafiz, 1983; Larik and Saheal, 1986; Azmi and Alam, 1990; De-Ming *et al.*, 1995; Boubakar, 1996). Salinity has also been shown to delay germination of crop seeds, including barley (Kabar, 1986) and wheat (Baykal, 1979; Larik and Hafiz, 1983; Begum *et al.*, 1992; Shalaby *et al.*, 1993; Farooq *et al.*, 1994; Muralia *et al.*, 1994).

2.2.1.2 Seedling emergence under sodic conditions

Delay and decrease in seedling emergence under sodic soil conditions have also been reported by various workers in different crops, such as groundnut (Singh and Abrol, 1985); sunflower (Chhabra *et al.*, 1979), rapeseed (Boem and Lavado, 1996), barley (Pearson and Berstein, 1958; Singh and Singh, 1990), sorghum, corn, ryegrass, safflower and tomatoes (Bains and Fireman,1964), oats (Ratner, 1935; Pearson and Berstein, 1958), clover, alfalfa (Bernstein and Pearson, 1956), cowpea (Singh *et al.*, 1980) and wheat (Ratner, 1935; Pearson and Bernstein, 1958; Sharma, 1991).

Due to the lower availability of water and possibly the direct effect of excess sodium on germinating seeds (Chhabra *et al.*, 1979), high sodicity delays the emergence of many crop seeds. Seedlings of groundnut, safflower (Bains and Fireman,1964), sunflower (Chhabra *et al.*, 1979), cowpea (Singh *et al.*, 1980), ber (*Ziziphus spp.)* (Mehta, 1982) and whistling pine *(Casuarina equisetifolia)* (Lalita *et al.*, 1994) have shown a delay of 3 to 4 days in emergence compared to the control soil treatments. In some crops such as oats (Pearson and Bernstein, 1958) sodicity retarded and decreased the final emergence %. However, in other crops such as sunflower (Chhabra *et al.*, 1979), barley and wheat (Pearson and Bernstein, 1958) sodicity delayed but did not decrease the final emergence %. Thorne (1944) and Moustafa *et al.* (1966) have also shown that the final germination % of wheat seeds was higher in sodic soil (32.8, 49.6 and 61.8 ESP) than in saline soil (total soluble salts of 1.23 to 2.4%).

The threshold level of sodicity at which germination and emergence are affected varies with crop species. In clover a decrease in germination appeared at ESP's above 25, whereas emergence in alfalfa was only decreased at an ESP of 51.5. Almost all seeds of barley and wheat had germinated after 12 days at high ESP (51.5), whereas only 63% of oat seeds germinated at the same ESP level. Tomato seeds rarely emerged at low ESP (28.5) and almost none emerged at high (51.5) ESP. Ryegrass seedlings emerged poorly at low ESP and did not emerge at high ESP (51.5). Sorghum was very sensitive at an ESP of 28.5 (Bains and Fireman, 1964).

2.2.2 Seedling growth and development

2.2.2.1 Seedling growth and development under saline conditions

There are many reports indicating that salinity decreases the growth and development of crop seedlings, including bean (Meiri *et al.*, 1970), barley (Greenway, 1965; Abou-Sharar, 1988; De-Ming *et al.*, 1995), sorghum (Mass *et al.*, 1989) and wheat (Baykal, 1979; Mass and Poss, 1989; Farooq *et al.*, 1994; De-Ming *et al.*, 1995; Ray and Khaddar, 1995; Boubakar, 1996). Differences in seedling growth and development under saline conditions among crop species and between varieties, particularly wheat, have also been reported (Baykal, 1979; Azmi and Alam, 1990).

2.2.2.2 Seedling growth and development under sodic conditions

Sodicity decreases the growth and development of plants. The effects of sodicity at early seedling stages can be very serious in some crops (rice, sesbania, tomato, pearl millet, and wheat etc) while in other crops such as sunflower the effects of sodicity are more serious at later stages, as they reach maturity (Chhabra *et al.*, 1979). The effects of sodicity on growth and development at the seedling stage have been examined in many crops by several workers including, barley (Bains and Fireman, 1964; Moustafa *et al.*, 1966), corn, sorghum, ryegrass, tomato (Thorne, 1944; Bains and Fireman, 1964) and cotton (Ray and Khaddar, 1993). Different crop species have shown differences in growth and development under sodic conditions. Corn seedlings have shown poor growth, deformed and folded leaves, death of central growing points and eventually death of seedlings at high sodicity (ESP 51.5). Emerged seedlings of sorghum have shown death even at low ESP (28.5). Ryegrass and tomato seedlings exhibited poor growth at medium sodicity (Bains and Fireman, 1964). In sunflower an ESP of 25 did not show any effect on the growth and development of seedlings up to 30 days, but growth decreased drastically after 48 days (Chhabra *et al.*, 1979).

Wheat is comparatively more susceptible to salt-affected soil conditions during the seedling stage (Bernstein, 1964; Dwivedi, 1979; Rowell, 1994) and possibly wheat seedlings cannot grow at or above an ESP of more than 55 (Abrol and Bhumbla, 1979).

Ray and Khaddar (1995) reported that sodicity decreased both shoot and root dry weight of wheat seedlings with every increase in ESP between 6 and 59.

Under sodic soil conditions the seedlings of wheat (Moustafa *et al.*, 1966), barley (Moustafa *et al.*, 1966) and lentil (Tewari and Singh, 1991) exhibited good early growth, but after two weeks the seedlings began to wilt and then died. It has been reported by Bewley and Black (1994) that seeds contain carbohydrates, fats, oils and proteins, stored as a source of food reserves, which support seedling growth at early stages. Once seeds germinate the seedlings first grow using the nutrients stored in the seed (endosperm). The reliance on the stored reserves diminishes as the seedling emerges above the soil surface and becomes photosynthetically active (i.e., autotrophic). At the same time as the leaves are expanding above the soil surface the roots of the seedlings are expanding below the soil surface, for uptake of nutrients and water. However, sodic soils, show toxicity of certain elements such as carbonates, bicarbonates and Na^+, poor soil structure and restriction in the availability of moisture which interfere with the growth and development of seedlings, with the result that they start wilting and die.

2.2.3 Ion uptake

Decrease in plant height, growth and yield under saline and sodic conditions are often attributed to the increase in uptake of toxic ions (usually Na^+ and Cl^-) and decreased uptake of other ions (K^+, Ca^{2+} and Mg^{2+}) which are important for metabolism. The following two sections are concerned with the effects of salinity and sodicity on the uptake of toxic ions and essential nutrients.

2.2.3.1 Ion uptake under saline conditions

It has been repeatedly demonstrated by several workers that under saline conditions the uptake of Na^+ and Cl^- is increased and uptake of K^+ and K^+/Na^+ ratio are decreased in germinating seeds (Begum *et al.*, 1992), and in stems and leaves of various crop plants including barley (Yeo and Flowers, 1982; Gorham, 1994) and corn (Shone *et al.*, 1969; Julie *et al.*, 1983). Evidence for this in wheat has also been given by many workers including Joshi *et al.* (1985); Khan *et al.* (1992); Chhipa and Lal (1993), Sastry and Parkash (1993), Leland *et al.* (1994), Barkat and Abdellatif (1996), Hamada (1996), Sharma (1996) and Gorham *et al.* (1997).

Like seedling emergence, growth and development, different plant species and varieties show large differences in Na^+ and K^+ accumulation and K^+/Na^+ ratio under saline conditions. Differences between wheat species and varieties in ion uptake have also been reported by many workers (Shah *et al.*, 1987; Azmi and Alam, 1990; Sastry and Parkash, 1993; Dvorak *et al.*, 1994; Ashraf and O' Leary, 1996; Gorham *et al.*, 1997). It has also been shown that a gene for K^+/Na^+ ratio discrimination in wheat resides in the D genome (Dubcovsky *et al.*, 1996) and greater discrimination has been shown by hexaploid bread wheat than by tetraploid durum wheat, lacking this genome (Gorham, *et al.*, 1997).

It is well documented that in salt-affected soils, stress on plants occurs due to effects both of ion composition (Na^+, Ca^{2+}, Mg^{2+}, K^+, SO_4^{2-}, CO_3^{2-}, HCO_3^- Cl^- and other ions) and concentration (Brady, 1990; Volkmar, 1998). Osmotic stress and toxicity of Na^+ and / or Cl^- have been suggested as two principal adverse effects of salinity on non-tolerant plants (Amtmann and Sanders, 1998). Ion deficiencies (particularly K^+ and Ca^{2+}), decrease of CO_2 fixation and inhibition of protein synthesis probably follow as secondary effects (Marschner, 1995).

It has been reported by Larcher (1995) that, if the adverse osmotic and specific ion effects of salt exceed the level tolerable to the plant, functional disturbances and injuries occur. The specific ion effect inhibits membrane activity (Crawford, 1989) and enzyme reactions (Marschner, 1995) that are dependent either completely on or stimulated by K^+ and other essential ions. Under saline conditions either due to ion imbalance (Na^+/K^+ imbalance in leaves), or due to water deficit, disturbances in protein metabolism also occur and hence accumulation of diamines, such as putrescine, cadaverine and polyamines occurs (Larcher, 1995).

Under saline conditions once saline solutes reach the leaf, salt ions can be accumulated in the apoplast (the network between the cells) or be isolated within the vacuole (Volkmar *et al.*, 1998). Accumulation of salt in the apoplast would gradually increase the osmotic gradient between the outside and inside of the cell. Salt ions must pass across the plasma membrane (separating the inside and outside of the cell) into the cytoplasm before entering the vacuole (Volkmar *et al.*, 1998). The rate of solute delivery across the plasma membrane must not exceed the rate of deposition into the vacuole to minimise the risk of salt damage. Otherwise it will result in the leakage of cytotoxic ions into the cytoplasm and apoplastic space outside of the cell, If this happens then toxicity will occur within the cell and cell expansion will cease entirely, due to the driving force for cell expansion with turgor pressure decreasing (Volkmar *et al.*, 1998). Na^+ is a cytotoxic ion at cytosolic concentration in excess of about 100 mM (Amtmann and Sanders, 1998).

2.2.3.2 Ion uptake under sodic conditions

In sodic soil conditions plants also show similar trends of high Na^+, low K^+ and low K^+/Na^+ ratio in leaf sap. However, in sodic soil conditions concentration of Ca^{2+} has been reported to be more markedly decreased than K^+ or other ions. The effects of sodicity on Mg^{2+} have not been frequently reported in these publications. These trends of ion uptake have been observed in many crops including barley (Mustafa *et al.*, 1966; Singh and Singh, 1990; Choudhary *et al.*, 1996), rice (Elgabaly, 1955; Anoop *et al.*, 1979), groundnut (Singh and Abrol, 1985), oilseed rape (Boem and Lavado, 1996), corn, safflower, rygrass and tomatoes (Bains and Fireman, 1964), red kidney beans, garden beets and Dallis grasses (Bower and Wadleigh, 1948), beans (Ayoub and Ishag, 1974), sunflower (Chhabra *et al.*, 1979), cowpea (Singh *et al.*, 1980), sorghum (Bains and Fireman, 1964; Monadjemi, 1977) and in some tree species (Mehta, 1982; Toky and Srinivasu, 1995).

There have been various reports of the same trends of ion uptake occurring in wheat (Mustafa *et al.*, 1966; Mehotra and DAS, 1973; Monadjemi, 1977; Joshi *et al.*, 1982; Gupta and Sharma, 1990; Chhipa and Lal, 1991; Padole, 1991; Yasin, 1991; Dvorak *et al.*, 1994; Choudhari *et al.*, 1996; Gorham *et al.*, 1997).

The concentration of individual and total ions varies with the advancement in time and age of plant. Barley (Mehotra and DAS, 1973; Singh and Singh, 1990), oats, pea, gram, lentil, cotton, maize, sorghum, rice and wheat crops have shown a decreasing trend in ion concentration with the advancement of time and age (Mehotra and DAS, 1973). Contrarily some other crops, such as groundnut (Singh and Abrol, 1985) and cowpea (Singh *et al.*, 1980) have shown an increase in Na^+ with plant age.

It is evident that because of differences in mobility the concentration of some ions does not remain the same in all plant parts, but varies in different parts. Rapid movement of Na^+ from roots to stem to petioles and leaves was noticed in injured drybean plants by Ayoub and Ishag (1974). Ca^{2+} is widely considered to be phloem immobile and incapable of translocation, Mg^{2+} is thought not to be similarly restricted, hence changes in Ca^{2+} can be expected more than Mg^{2+} in plants (Lazof and Bernstein, 1998). Beans and garden beet leaves, especially the top parts, have shown marked decreases in Ca^{2+} and Mg^{2+} with increasing Na^+ supply, while the roots did not show decrease in the contents of Ca^{2+} and Mg^{2+} in the presence of high exchangeable Na^+ (Bower and Wadleigh, 1948). Chhabra *et al.* (1979) demonstrated that the concentration of Na^+ in sunflower decreased in the order of stem >lower leaves> flowerhead and was present in traces in grains. A gradient in Na^+ distribution, especially within the sensitive wheat varieties, in the order of stem> leaves> earheads has also been demonstrated by Sharma (1991). However, because of competition between K^+ and Na^+ under sodic soil conditions, wheat grains can show significant decrease in K^+ contents (Cope *et al.*, 1953; Haqani *et al.*, 1984).

The effects of soil sodicity on plants also depends on atmospheric temperature and humidity. High temperatures coupled with low humidity have been shown to enhance translocation of Na^+ from roots to shoots of bean plants, possibly because of increased transpiration, resulting in the complete death of plants at high temperature (Ayoub and Ishag, 1974). Plants of dwarf kidney beans grown at 30, 45 and 60 ESP have shown the symptoms of water stress during warm days.

2.2.4 Uptake of essential nutrients

2.2.4.1 Uptake of N, P and essential micronutrients under saline conditions

Under saline soil conditions the uptake of nutrient ions is decreased, which causes nutritional disorders in the plants, viz., toxicity of B, Na^+ and Cl^- and deficiency of N, P and micronutrients (Zn^{2+}, Cu^{2+}, Mn^{2+}, Fe^{2+} etc).

There are several reports which show that soil salinity decreases NO_3^- uptake by plants including barley (Helal *et al.*, 1975; Aslam *et al.*, 1984; Ward *et al.*, 1986; Klobus *et al.*, 1988), cotton (Silberbush and Ben-Asher, 1987) and wheat (Mashhady *et al.*, 1982; Shaviv and Hagin, 1993). However, there are some reports which show a stimulatory effect of salinity on NO_3^- uptake by plants (Kafkafi *et al.*, 1982; Feigen *et al.*, 1987). The form of N supplied to the plants could be an important factor. Leidi *et al.* (1991) reported that although the form of N applied to salt stressed maize and wheat did not show any influence on yield, the plants fed with NH_4^+ were more sensitive to salinity than NO_3^- fed plants. The total N content in all parts of the wheat plants is decreased by high salinity.

The uptake of P by plants under saline conditions is more complex compared to uptake of N. It depends on plant species, variety, age of plants, the composition and level of salinity and the concentration of P in the rooting medium. Thus the effects observed mainly depend on the plant species and the conditions of the experiment. Various authors have demonstrated that added P in the medium either increased or decreased or had no effect on crop growth and yield (Champagnol, 1979). Increasing P supply had no effect on the salt resistance of plants (Champagnol, 1979). Deficiency of P in plants growing in saline conditions may occur because P in the presence of Ca^{2+} ions forms calcium phosphates in the soil solution which is insoluble and unavailable to plants (Awad *et al.*, 1990).

The concentration of micronutrients in the soil solution under saline conditions depends on physical and chemical factors, especially soil pH. It has been concluded by many workers that the uptake of micronutrients in plants varies with crop species. In some crops the uptake of micronutrients is increased while in other crops it is decreased. For example Zn^{2+} uptake increased in barley (Hassan *et al.*, 1970), bean (Doering *et al.*, 1984), tomato and soyabean (Mass *et al.*, 1972), but it decreased in corn (Hassan *et al.*, 1970) and mesquite (Jarrell and Virginia, 1990). Similarly Mn^{2+} and Fe^{2+} contents increased in some crops, and decreased in other crops. Mn^{2+} content was increased in barley (Hassan *et al.*, 1970), sugar beet (Khattack and Jarrel, 1989) and tomatoes (Mass *et al.*, 1972), and decreased in pea (Dahiya and Singh, 1976) and corn (Hassan *et al.*, 1970). Pea (Dahiya and Singh, 1976) and tomato (Mass *et al.*, 1972) have shown higher Fe^{2+} uptake whereas, barley and corn have shown lower Fe^{2+} under saline conditions.

Evidence in wheat also shows a decreasing trend of Zn^{2+}, Mn^{2+}, Cu^{2+} and Fe^{2+} under high soil salinity conditions but no effect of low salinity has been shown (Padole *et al.*, 1995).

2.2.4.2 Uptake of N, P and essential micronutrients under sodic conditions

Sodicity inhibits the uptake of N, P and micronutrients (Zn^{2+}, Cu^{2+}, Mn^{2+}, Fe^{2+} and MoO_4^{2-}) by plants. The decrease in nutrient uptake can be the result of deterioration in soil physical conditions and the nutrient imbalance created by high pH, excessive concentration of some ions (Na^+ and HCO_3^-) and low O_2 availability in the root zone, making the soil environment unfavourable for the proper growth of plants (Singh and Totawat, 1994). The effects of sodicity on nutrient uptake by plants, including N, P, and micronutrients (Zn^{2+}, Cu^{2+}, Mn^{2+}, Fe^{2+} and MoO_4^{2-}) have been investigated in different plant species, especially in young seedlings of corn, sorghum, safflower, ryegrass and tomatoes (Bains and Fireman, 1964), tree species (Mehta, 1982; Toky and Srinivasu, 1995), groundnuts (Singh and Abrol, 1985), rice (Annop *et al*., 1979), sunflower (Chhabra *et al*., 1979) and cowpea (Singh *et al*., 1980). It has been shown from these reports that in some plant species (corn, sorghum, safflower, ryegrass and tomatoes) the uptake of N increased under sodic soil conditions, but it decreased in groundnuts. On the other hand in some tree species N content increased up to an ESP of 30 and beyond that N content showed a sharp decline. Similarly P content was also decreased by sodicity in some crops such as corn, sorghum, safflower, ryegrass, and tomatoes but not in sunflower where P moved to upper parts. Generally the content of Zn^{2+} (except in sorghum), Cu^{2+} (except in tomatoes), Mn^{2+} and Fe^{2+} (except in sunflower, where they increased) decreased in sodic soil treatments. However, sodicity had no effect on the uptake of Zn^{2+}, Cu^{2+}, Mn^{2+}, Fe^{2+} and MoO_4^{2-} in groundnuts.

The uptake of N, P, Zn^{2+}, Cu^{2+}, Mn^{2+}, Fe^{2+} and MoO_4^{2-} by wheat under sodic soil conditions has also been investigated. The reports regarding N concentration presented by various workers are in contrast. For example, Chhipa and Lal (1991) concluded that N content in grain and straw increased with increasing sodicity. However, there have been some other reports (Sharma and Swarp, 1989; Padole, 1991), which show decrease in N content with increasing ESP level.

Some reports (Sumner and Naidu, 1998) show that P is not a major fertility constraint in sodic soils, and the crop response to P in sodic soils is very rare, whereas, in other reports sodicity has been shown to decrease uptake of P in plants, especially in wheat plants (Sharma and Swarp, 1989; Chhipa and Lal, 1991; Padole, 1991). Although, information on micronutrient dynamics in relation to soil-plant relations in sodic soils is limited, sodicity has also been shown to decrease uptake of Zn^{2+}, Cu^{2+}, Mn^{2+} and Fe^{2+} in plants (Padole, 1991; Sumner and Naidu, 1998). However, in the presence of impeded drainage the content of Fe^{2+} and Mn^{2+} in sodic soils increased, with the result that they may become toxic, resulting in increased uptake in wheat plants (Sharma and Swarp, 1989).

2.2.5 Plant growth and development

2.2.5.1 Plant growth and development under saline conditions

It is widely accepted by several workers that many crops are very salt-sensitive at early growth stages. However, it is not the case in all crops. Some crops are able to germinate well at salinity levels higher than those they can tolerate at later stages. For example, peanut has shown 50% emergence at high salinity (13 dSm^{-1}), but it showed 50% reduction in seedling growth and 50% reductions in yield at low salinity levels (7.5 dSm^{-1} and 4.7 dSm^{-1} respectively) (Shalhevet, 1989). In wheat salinity is more injurious after emergence, before tillering and at the booting stage (De-Ming *et al.*, 1995) than at later growth stages (Qureshi *et al.*, 1990). Several studies have shown that tiller production is decreased in wheat under saline conditions (Mass *et al.*, 1990; Mass and Grieve, 1990; Nicolas *et al.*, 1993).

The effect of salinity is more injurious to shoot growth than to root growth (Delane *et al.*, 1982). Salinity significantly reduced the vegetative growth of wheat (Mashhady and Heakal, 1983). Leaves of non halophytes grow more slowly in salt stressed conditions than in normal conditions (Munns and Termaat, 1986). Over a long period (weeks, months) the concentration of salts increases in the shoot, especially in the fully expanded older leaves. Hence these leaves usually die before the young leaves (Greenway and Munns, 1980). Due to the death of a considerable number of old leaves, leaf production decreases, which results in decreased photosynthetic leaf area and also reduction in carbohydrate production. If the amount of carbohydrate in plants falls below a level capable of sustaining further growth, the death of plants occurs (Munns and Termaat, 1986). It has been suggested that saline salts induce the roots to send a growth regulator-like chemical signal to the shoot that leads to shoot growth inhibition (Munns and Termaat, 1986).

2.2.5.2 Plant growth and development under sodic conditions

Sodicity has been shown to reduce growth and development of several plant species, including rice (Anoop *et al.*, 1979), tomatoes, ryegrass and barley (Carr and Greenland, 1975), bean (Ayoub and Ishag,1974), sorghum (Monadjemi, 1977; Raghuwanshi *et al.*, 1989), cotton (Raghuwanshi *et al.*, 1989), oilseed rape (Boem and

Lavado, 1996), groundnut (Singh and Abrol, 1985), barley (Choudhary *et al.*, 1996), *A. nilotica* (Toky and Srinivasu, 1995) and ber (*Ziziphus jujubi*) (Mehta, 1982).

The effects of sodicity on growth and development of wheat plants have also been widely investigated. Sodicity has been shown to cause reductions in wheat height and growth (Hummadi, 1977; Rauf *et al.*, 1978; Chhipa and Lal, 1991; Singh *et al.*, 1992).

Under sodic soil conditions the uptake of water from soils is decreased, resulting in induced drought. As a consequence leaves become thicker, and fewer and smaller leaves are produced, leaf injury symptoms may be evident and ultimately premature leaf death may occur. Reduction in leaf area occurs, because of reduced cell enlargement. Complete death of plants can also occur within 7 to 10 days from the appearance of the first symptoms of injury (Ayoub and Ishag, 1974). Decreases in leaf production and leaf area with increasing sodicity have also been found in other species grown under sodic soil conditions, for example the plants of 5 months old trees (Toky and Srinivasu, 1995) and barley (Choudhary *et al.*, 1996). Development of yellowing and burning of leaves has also been recorded (Elgabaly, 1955).

Decreased tiller production and increased tiller death in wheat plants has also been recorded under sodic soil conditions (Rauf *et al.*, 1978; Haqani *et al.*, 1984; Joshi *et al.*, 1985; Sharma, 1988; Chhipa and Lal, 1991; Singh *et al.*, 1992; Verma *et al.*, 1993). Even at low ESP (22) tillers in wheat did not survive (Joshi, 1976). This is the main factor for yield reduction even at low sodicity.

Roots have also been shown to be seriously affected by sodic conditions. Elgabaly (1955) found that barley plants grown in a resin-based pure sodium system had very short, thick, and brown roots with little branching. Roots of *Brassica napus* (Joshi *et al.*, 1985), barley (Choudhary *et al.*, 1996) and some tree species (Mehta, 1982; Toky and Srinivasu, 1995) did not show successful penetration and growth in sodic soils, compared to normal soils.

2.2.6 Yield and yield components

2.2.6.1 Yield and yield components under saline conditions

Soil salinity is a major constraint that limits yield and total dry matter production. Salinity decreases the grain yield of cereals (Ayer *et al.*, 1952; Joshi *et al.*, 1979; Qureshi *et al.*, 1980; Gorham *et al.*, 1985; Mashhady and Heakal, 1983; Ashraf and McNeilly, 1988; Mass and Grieve, 1990; Iqbal, 1992; Maliwal and Sutaria, 1992; Padole *et al.*, 1995; Gorham *et al.*, 1997). Salinity also reduces the dry matter production of both shoot and root (Srivastava *et al.*, 1988; Maliwal and Sutaria, 1992). However, the decrease in shoot production is more pronounced than root production (Cordovilla *et al.*, 1994). Straw yield is more sensitive to salinity than grain yield especially at low levels (Pearson, 1959; Francois *et al.*, 1986, 1989).

Grain yield in cereals is a function of number of heads per unit area, number of kernels per head and kernel weight (yield components). Significant reduction in all yield components of wheat has been widely reported (Baykal, 1979; Mashhady and Heakal, 1983; Mass and Grieve, 1990; Francois *et al.*, 1994; Mass *et al.*, 1996). Differences between varieties and species in yield and yield components have also been demonstrated by several workers (Baykal, 1979; Mashhady and Heakal, 1983; Gorham *et al.*, 1997).

2.2.6.2 Yield and yield components under sodic conditions

Sodicity has been shown to decrease the economic yield of several crops including, sesbania and rice (Mehotra and DAS, 1973; Anoop *et al.*, 1979; Gupta and Sharma, 1990), oilseed rape (Boem and Lavado, 1996), groundnut (Singh and Abrol, 1985), barley (Mehotra and DAS, 1973; Choudhary *et al.*, 1996), sunflower (Chhabra *et al.*, 1979), oats, pea, gram, maize and sorghum (Mehotra and DAS, 1973), cotton (Mehotra and DAS, 1973; Raghuwanshi *et al.*, 1989) and lentil (Mehotra and DAS, 1973; Tewari and Singh, 1991). There are several reports showing that sodicity decreases the straw and grain yield of wheat (Mehotra and DAS, 1973; Hummadi, 1977; Nitant and Chillar,1983; Chhipa and Lal, 1991; Padole, 1991; Sharma; 1991; Gill *et al.*, 1992; Khan *et al.*, 1992; Singh *et al.*, 1992; Verma, 1993).

The decreases in grain and straw yield of different crops have been shown to vary with ESP (Mehotra and DAS, 1973; Pearson and Bernstein, 1958; Gupta and Sharma, 1990). The threshold value of ESP at which yield starts to decrease and the value of ESP at which yield is decreased by 50 % vary with crop species. Values for these for crops in India are given in Table 2.2 (Gupta and Sharma, 1990).

There is a evidence that different varieties of crops show differences in economic yield under sodic soils, including sorghum (Raghuwanshi *et al.*, 1989), barley (Abou-Sharar, 1988; Qadar; 1990; Singh and Singh; 1990; Choudhary *et al.*, 1996) and cotton (Raghuwanshi *et al.*, 1989). Differences in straw and grain yield between wheat species and varieties have also been recorded by various workers (Qureshi *et al.,* 1980; Singh, 1989; Gupta and Sharma, 1990; Sharma, 1991; Khan *et al.*, 1992; Choudhary *et al.*, 1996). Durum wheat has been reported to be more sensitive to increasing ESP than bread wheat (Rana *et al.*, 1980; Joshi *et al.*, 1982; Singh and Rana, 1985; Gorham *et al.*, 1997) At equal ESP (30) the reduction in dry matter production has been found to differ between three wheat species (Joshi *et al.*, 1982). The greatest reduction was shown by *Triticum monococcum*, a small reduction by *T. durum* and least reduction by *T. aestivum*.

Sodicity has been shown to decrease all yield contributing components in many crops including reduction in number of pods and number of grains per pod of groundnut (Singh and Abrol, 1985), and number of panicles of sorghum (Raghuwanshi *et al.*, 1989). Decrease in number of seeds, number of pods per plant and 1000 grain weight in lentil (Tewari and Singh, 1991) and in oilseed rape (Boem and Lavado, 1996) have been recorded. Decrease in 1000 grain weight in barley has also been reported by Choudhary *et al.* (1996).

There are many reports showing that sodicity decreases all yield components of wheat. Sodicity even at low ESP (22) level (Joshi, 1976) decreased the number of ear (fertile) and non ear bearing tillers (Haqqani *et al.*, 1984; Singh *et al.*, 1992 Singh *et al.*, 1993). High sodicity (approximately ESP 36) (Joshi, 1976) reduced all yield components of wheat, including number of spikelets/ear and 1000-grain weight (Haqqani *et al.*, 1984; Gill *et al.*, 1992; Khan *et al.*, 1992), ear length (Sharma, 1988), harvest index (Singh *et al.*, 1988) and 1000-grain weight (Khan *et al.*, 1992). Compared to grain weight, sodicity resulted in a marked decrease in number of grains per plant (Sharma, 1991).

Varietal variability in yield components has also been shown in wheat. Some varieties have shown higher 1000 grain weight than others under sodic soil conditions (Singh and Rana, 1985; Gill *et al.*, 1992). The effect of sodicity on grain yield also depends on varieties and species. In some varieties and species the grain yield reduction starts from ESP 14 whereas in other varieties grain yield reduction starts from ESP 18 (Sharma *et al.*, 1991). Loss of grain yield in sodic soils also varies with weather conditions. Low seed yield of dry beans was recorded from plants sown in warm days (Ayoub and Ishag, 1974).

Table 2.2. Threshold and ESP_{50} of crops for medium (sandy loam) textured soils (Gupta and Sharma, 1990)

Crop	Botanical name	$ESP_{threshold}$	ESP (50 % yield decrease)
Barley	*Hordeum vulgare*	8.5	22.3
Cowpea	*Vigna unguiculata*	13.5	19.0
Sesbania	*Sesbania aculeata*	46.9	67.7
Gram	*Cicer arietinum*	7.7	17.7
Groundnut (peanut)	*Arachis hypogaea*	8.0	29.7
Guar (Clusterbean)	*Cyamopsis psoralodes D. C.*	11.9	27.5
Lentil	*Lens esculentum*	4.9	14.0
Linseed	*Linum usitatissinum L.*	13.3	25.0
Pearlmillet	*Pennisetum typhoideum*	13.6	32.8
Raya (Indian mustard)	*Brassica juncea L.*	7.6	70.1
Rice	*Oryza sativa*	24.4	80.0
Rye	*Secale cereale*	11.0	30.2
Sesamum	*Sesamum indicum*	9.0	22.8
Soyabean	*Glycine max*	8.0	22.3
Sunflower	*Helianthus annus L.*	11.3	56.8
Safflower	*Carthamus tinctorius*	7.6	17.2
Wheat	*Triticum aestivium*	16.4	40.2
Pea	*Pisum sativum*	7.7	19.9
Onion	*Allium cepa*	9.8	32.5
Garlic	*Allium sativum*	9.5	37.3

ESP_{50} = the ESP at which the yield is 50 % of the control value.
Threshold = beyond which crop yield declined.

Although sodicity decreases crop yield, there is some evidence (Mehotra and DAS, 1973) showing that at low ESP level some crops (wheat, barley, oats, cotton, maize, sorghum and paddy) have shown a slight increase in their yield but other crops (pea, gram and lentil) have shown a significant yield decrease at low sodicity. The reports regarding the effects of sodicity on wheat are not consistent, because some workers (Joshi, 1976) indicated that at ESP 22 yield increased compared to the control treatment, whereas, others (Gupta and Sharma, 1990) concluded that ESP 16.4 is a threshold for wheat.

2.2.7 Salt tolerance

2.2.7.1 Salt-tolerance under saline conditions

Studies on the problems of salinity were started in 1891, by Schimper's investigations performed with mangrove plants (Baykal, 1979). During the last 40 years, much of the research has been directed towards the investigation of salt-resistant and susceptible plants. It has been concluded that salt-tolerance in plants varies with growth stages. Plants are often salt-tolerant during germination, become more sensitive during the emergence and young seedling stages and become more tolerant through the reproductive stage with the exception of anthers (Crawford, 1989). It has been noted by several workers that compartmentation of ions (Gorham, 1994), and maintenance of high K^+/Na^+ ratio (Crawford, 1989) are the important plant attributes associated with salt tolerance mechanisms in cereals (glycophytes). Much progress has also been made in investigating the salt-tolerance of wheat species and varieties. It has been concluded by many workers that salt-tolerant wheat species and varieties accumulate less Na^+ and more K^+, thus they show higher K^+/Na^+ ratio. Higher seedling emergence, growth and yield have also been recorded in salt-resistant wheat species and cultivars than in salt-sensitive wheat (Sayed and Mashhady, 1983; Mashhady *et al.*, 1985; Singh *et al.*, 1988; Li and Liu, 1993; Chhipa and Lal, 1995; Farooq *et al.*, 1995; Muhammad *et al.*, 1995; Sharma, 1996). *Triticum aestivium* has been found to be more salt-resistant than *Triticum durum* under saline conditions (Joshi *et al.*, 1985).

2.2.7.2 Salt-tolerance under sodic conditions

Sodicity resistant species and varieties accumulate less Na^+, more K^+ and more Ca^{2+} in leaves and stems than sensitive ones. However, the reports for Mg^{2+} contents are not consistent. Resistant plants also show higher leaf or stem K^+/Na^+ and Ca^{2+}/Na^+ ratios than sensitive plants. These trends have been reported in many plants including beans (Ayoub and Ishag, 1974), barley (Sudhaya *et al.*, 1992; Choudhary *et al.*, 1996) and tree species (Toky and Srinivasu, 1995). Sodicity tolerant plants accumulate more Na^+ in their roots than in stems and leaves, compared to sensitive plants, which show rapid movement of free Na^+ ions from roots to stem and leaves. However, the resistant plants have not shown differences in other cation contents in roots (Ayoub and Ishag, 1974).

Varieties of wheat tolerant to sodicity have also shown ability to develop a mechanism to restrict the uptake of toxic ions. Wheat varieties tolerant to sodicity may have low root permeability to sodium salts which prevents excessive accumulation of toxic ions, and they may accumulate more Ca^{2+} instead of Na^+ (Chhipa and Lal, 1991).

Sodicity tolerant wheat cultivars accumulate less Na^+ and more K^+ and they also have higher K^+/Na^+ ratio in leaves (Joshi *et al.*, 1979; Sharma 1991) and grains (Khan *et al.*, 1992) than sensitive cultivars. In sensitive wheat cultivars lower leaves did not survive, indicating the translocation of Na^+ from roots to leaves. *Triticum aestivium* has been shown as a more resistant wheat to sodic soil conditions as it absorbs less Na^+ and more K^+ than *Triticum durum* (Joshi *et al.*, 1982; Dvorak *et al.*, 1994; Choudhary *et al.*, 1996; Gorham *et al.*, 1997).

Sodicity tolerant wheat plants have shown larger, more penetrating root systems (Joshi *et al.*, 1985) and due to their larger leaf canopy and longer root system they maintain higher rates of transpiration (Choudhary *et al.*, 1996) than sensitive wheat plants. This characteristic has also been reported in sodicity resistant barley cultivars (Choudhary *et al.*, 1996). The adverse effects of high sodicity on root growth of sensitive plants may occur due to an accumulation of toxic ions or to decreased absorption of essential nutrients, decreased permeability to air and water and depressed colloidal structure of sodic soils (Toky and Srinivasu, 1995). Although wheat has been shown as a tolerant crop to an ESP between 40 and 60, it is not tolerant to adverse physical condition of sodic soil at the same ESP levels (Table 2.3).

Bicarbonate ion toxicity has also been implicated in the failure of crop growth in sodic soils. The bicarbonate ion mainly inhibits the uptake and translocation of ions in plants, especially the uptake and translocation of iron in some plant species eg. calcifuge plants (Woolhouse, 1966), which show symptoms of lime-induced chlorosis. It has been investigated by some workers that in the presence of bicarbonate ions some plant species such as beans and Dallis grasses are very sensitive while rhodes grasses and beets are relatively tolerant (Gauch and Wadleigh, 1945; Bower and Wadleigh, 1948). In the presence of bicarbonate ion bean plants shown less Ca^{2+} and more K^+ than control plants, while the main effect shown by bicarbonate in beets is to decrease Mg^{2+} and increase the Na^{2+} content.

Table 2.3. Tolerance of various crops to exchangeable sodium percentage (ESP) (Pearson, 1960 as reported in Sumner and Naidu, 1998)

Tolerance to ESP	Crop	Growth response under field conditions
Extremely sensitive (ESP 2 to 10)	Deciduous fruits Nuts Citrus Avacado	Sodium toxicity symptoms even at low ESP values
Sensitive (ESP 10 to 20)	Beans	Stunted growth at low ESP values even though the physical conditions of the soil may be good
Moderately tolerant (ESP 20 to 40)	Clover Oats, Tall fescue, Rice and Dallis grass	Stunted growth due to both nutritional factors and adverse soil conditions
Tolerant (ESP 40 to 60)	Wheat Cotton Alfalfa Barely Tomatoes	Stunted growth usually due to adverse physical conditions of soil
Most tolerant (ESP > to 60)	Tall wheatgrass Rhodes grass	Stunted growth usually due to adverse physical conditions of soil

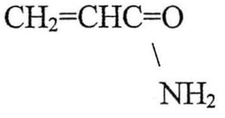
The difference between plant to resistance to a wide range of stresses is dependent on their ability to sense and respond appropriately. Such responses are often controlled by a number of genes (Jenkins, 1998). The differences in wheat species and varieties in ion uptake, growth and yield under stress conditions are also controlled by a number of genes (Singh, 1989; Ahsan, 1996), but their exact location and modes of action are still not clear to scientists (Gorham, 1992). Considerable progress has been made in identifying the location of genes associated with salt-tolerance mechanisms in wheat.

During recent years there has been some success in transferring the salt-resistance genes into salt-sensitive crops to make them salt-resistant. For instance, the Kna1 gene has been introduced by Dvorak *et al.* (1994) into durum wheat genotypes, which are now salt-resistant, compared to their parents.

2.3 Polymers

Another effect of sodicity is to cause deflocculation of soil colloids, resulting in deterioration of soil structure, which also adversely affects plants. In the experiments reported in the thesis a polyacrylamide soil conditioner has been used to improve the structure of sodic soils. This section briefly reviews polymers in general, and their role in soil improvement.

A polymer is defined as a substance composed of very large molecules (macromolecules). The molecular structure is a chain of many monomers (small molecules that bind together to form a polymer) joined by covalent bonds of carbon atoms ($-CH_2-CH_2$) (Campbell, 1994; Grula *et al.*, 1994). Chemical reactions between monomers occur both in nature and man-made conditions. If polymers are made by reacting monomers under controlled circumstances, they are called synthetic polymers. Several types of synthetic polymer have been used for achieving different objectives. A polyacrylamide is one of the most common synthetic polymers. Polyacrylamides (PAMs) are polymers whose monomeric unit is acrylamide (Campbell, 1994).



$$CH_2{=}CHC{=}O \quad \backslash \quad NH_2$$

2.3.1 History of polymers

Already in prehistoric times humans used natural polymeric materials, such as wood and horn. In the nineteenth century these natural polymers could be modified, but it was not until the beginning of this (twentieth) century that the first fully synthetic polymers appeared. During the Second World War the use of synthetic polymers as soil conditioners became clear when they were used to stabilise the soil of landing fields and roads. After this war polymers started being used in other areas, like agriculture, and ever since, a lot of research has been done to investigate their benefits. However, the use of polymers in general agriculture is still limited, due to high polymer cost and the high application rates required (Sojka and Lentz, 1994).

2.3.2 Safe use of polymers

PAMs are considered to be very safe when used as directed. The toxicity of PAMs to mammalian systems and fish is minimal. The toxic limit for animals has been suggested to be $LD_{50} > 5mg\ kg^{-1}$ and for fish $LC_{50} > 100mg\ L^{-1}$ (Barvenik, 1994). No environmental harm to aquatic organisms has been documented. In studies using rats they did not cause any damage to reproductive systems, or problems following skin contact. When applied to crops of corn, oats and carrots no toxicity was found in the harvested products.

2.3.3 Properties of polymers

When applying synthetic polymers to improve soil structure, the properties of polymers must be considered. Since the introduction of synthetic polymers in the field of soil science, there has been some work to test their qualities. Essential aspects of the ideal polymer are a slow rate of destruction in soil, no toxic effects on animals and plants, no disturbance of the microbial population (like growth of nitrogen fixing bacteria and sulfur bacteria) and good aggregating abilities (Quastel, 1952; Martin, 1953; Barvenik, 1994).

Anionic PAMs degrade in soil with the advancement of time, as a result of mechanical degradation, chemical and biological hydrolysis, sunlight, salt and temperature effects (Barvenik, 1994). Through a natural way it takes decades to stabilise the soil aggregates, whereas by using polymers in a proper way it can be achieved in only hours or days. Their effects can also last longer. During studies it was noticed that field and greenhouse soils treated with synthetic resins showed marked physical improvement beyond the second growing season (Martin, 1953). It has been concluded that the rate of application of PAM, level of aggregation initially obtained, type of crop grown, kind and amount of clay present, all affected the longevity of the treatment. Biological deterioration of these components is very slight and even in some cases the effect of polymers on silt loam and clay loam soil remained persistent up to 6 years (Greenland, 1963).

2.3.4 Polymers in soils

For increasing aggregate stability, preventing clay dispersion, decreasing crusting in hard and Na^+ deteriorated soils, organic natural and synthetic polymers have been used by various workers (Allison, 1952; Quastel, 1952; Martin, 1953; Helalia and Letey, 1989; Saleh and Letey, 1990; Morsey *et al.*, 1991; Metwally *et al.*, 1992; Waller and Wallender, 1993; Grula *et al.,* 1994; Letey, 1994; Nadler, 1994; Shainberg and Levy, 1994; Sojka and Lentz, 1994; Barzegar *et al.*, 1997, Ben-Hur and Keren, 1997; Levy and Miller, 1997). However, very few studies have investigated the potential use of polymers for improving plant performance in sodic soils in the presence of high exchangeable sodium and improved soil structure.

Sodic soils can slump badly with no aggregation at the surface, and show dispersion in clay and organic matter with slow water infiltration. This can easily cause surface waterlogging for long periods. Addition of polymers can overcome these problems (Pearson and Bernstein, 1958; Grable, 1966; Greenwood, 1971; Carr and Greenland, 1975).

Water soluble polymers or polyacrylamides can counter the effects of deteriorated soil structure (Carr and Greenland, 1975) and compact surfaces resulting from a decrease in organic matter content. PAM minimises water run-off, erosion and crusting, and stabilizes soil structure (Farm Chemical Handbook, 1986). Soil texture, clay-mineral make-up and organic matter content influence the effectiveness of conditioners. For example, aggregation has been found to be greater in fine-textured soils (Allison, 1952; Martin, 1952).

2.3.4.1 Polymers and soil biology

PAM can serve as an energy source for nitrogen fixing and sulfate reducing bacteria and it has been shown that PAMs enhance the growth of these bacteria. Two possible mechanisms by which these bacteria may do this in anaerobic conditions, are:

(1) - assimilation of NH_4^+ by the bacteria which results in further chemical hydrolysis of amide groups on the PAM molecule; or

(2) - micro organisms growing on PAM produce an extracellular enzyme (whose natural substrate is not PAM) that catalyses the release of NH_4^+ from the PAM molecule. Barvenik (1994) observed that following an application of PAM there was an increase in

total soil beneficial fungi and bacteria counts, such as nitrogen-fixing bacteria (*Azotobacter*) and nitrifying bacteria, whereas the nematode population was reduced and restricted in its activity.

2.3.4.2 Polymers and physical properties of soil

Polymers influence the physical properties of soil. Penetration of the polymers into the soil depends on their molecular weight (Letey, 1994). Soil conditioners increase soil aggregation and related properties (porosity and permeability). In particular polymers increase the % of large crumbs (aggregates larger than 2 mm) stable in water. The total aggregation can also be increased by over 80% (Martin, 1953). Polymers do not create new aggregates, but they preserve the aggregates in the physical form existing at the time of application (Cook and Nelson, 1986). This contradiction may be due to polymer application under different soil conditions.

2.3.4.3 Mechanisms of polymer adsorption in soil

Generally the properties of synthetic polymers are not very different from those of natural polysacchrides, thus the mechanisms of soil aggregation are probably the same as with natural polymers (Harris *et al.*, 1966).

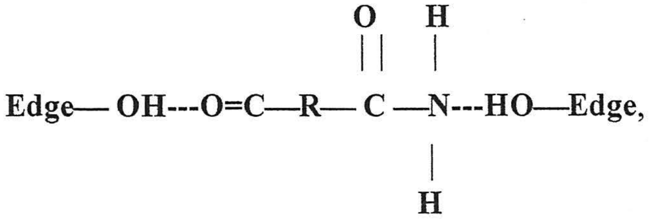
The inter-particle mechanisms between clay particles and polymer (especially anionic) molecules have been reported by Harris *et al.* (1966). Mechanisms involved in aggregation are:

(1) formation of a series of hydrogen-bonds between the polymer hydroxyl groups and the surface oxygen of the silicates sheets,

e.g. **Face Si—O---HO—R—OH---**

(2) hydrogen bonding between edge hydroxyl and polymer carbonyl or amide group,

e.g.



$$\text{Edge}—\text{OH---O=C}—\text{R}—\overset{\displaystyle\text{O}}{\overset{||}{\text{C}}}—\underset{\underset{\displaystyle\text{H}}{|}}{\overset{\overset{\displaystyle\text{H}}{|}}{\text{N}}}\text{---HO}—\text{Edge},$$

R denotes the organic polymer with axis horizontal or perpendicular to clay domain (group of clay crystals)

(3) anion exchange between hydroxyl groups of clay particles and carboxyl groups of the polymer,

e.g. $\mathbf{Al - OH_2^{+} ---- {}^{-}OOC - R - {}^{-}OOC^{-} ---}$,

(4) formation of peripheral complexes between the polymer and the edge faces of 2 or more clay crystals,

(5) involvement of non specific Van der Waals forces in the adsorption (Van der Waals attraction between faces and polymer),

(6) formation of polymer bridges between 2 or more clay particles and adsorption of hydroxyl or amide groups on solid surfaces to form bridges between more than one solid particle and the formation of polymer bridges between the crystals of expanding (montmorillionite) clays.

The adsorption of organic polymers on clay also depends on the nature of the polymer's charge. Organic cationic and uncharged polymers are adsorbed on the basal surfaces of clay minerals, causing an increase in the *c-axis* spacing of expanding-lattice type clays, such as montmorillonite. However, the anionic polymers do not change the *c-axis* spacing of expanding-lattice type clay minerals, and they are adsorbed on to the edge surface rather than between the negatively charged basal plates (Greenland, 1963). The divalent cationic link between polymer carboxyl and the negatively charged clay surfaces has also been suggested by Russell (1938) as reported in Harris *et al.* (1966). Formation of bonds between carboxyl groups of anionic polymers and the multivalent cations on the exchange complex of clay surfaces have also been reported by Peterson (1947).

Several investigators have reported that aggregation by anionic polymers is dependent on the clay and silt contents of soil. Aggregation increased with increased clay and silt contents (Martin *et al.*, 1952; Allison, 1952). Contrarily, Laws (1954) reported that the aggregating effectiveness of polymers decreased as clay content increased. Similarly, Jacobson and Swanson, (1958) reported that initial stabilising effect of HPAN (hydrolysed polyacrylonitrile) was greatest in sandy soil, but longevity of the effect was greatest on silty and clayey soils. Clay minerals and anionic polymers are also believed to form peripheral complexes in which a link occurs between the polymer and the edge faces of 2 or more clay crystals. Polymers do not penetrate the aggregates but form a network around the aggregates, a network of tightly adsorbed molecules which protects the aggregates from dispersion (Letey, 1994).

2.3.4.4 Effective rates and application of polymers

Aggregation of soils is directly related to the concentration of applied polymer. Excessive concentration of polymers should be avoided (Harris *et al.*, 1966) whereas, diluted and lower concentrations of polymers have been recommended by various workers (Martin, 1953; Harris *et al.*, 1966; Shainberg and Levy, 1984; Wallace *et al.*, 1986). A concentration of 1% of PAM is more effective than one of 5% (Wallace *et al.*, 1986), and small rates of application (10 to 20 kg ha^{-1}) have been found more effective and economical than higher rates (Shainberg and Levy, 1984). At a concentration of >0.2 % anionic polymer it appears that one or more polymer molecules adsorb onto single clay particles so that interlinkage of clay particles is limited (Harris *et al.*, 1966). The rate of treatment depends upon the desired depth for aggregation and the type of soil. For maximum efficiency the application of liquid chemicals is most suitable for surface treatments, but dry powder is better for depth or incorporation treatments (Martin, 1953).

2.3.5 Polymers for crop production

2.3.5.1 Effects of polymers on seedling emergence and growth

The presence of excessive amounts of exchangeable Na^+ on clay complexes can cause swelling and dispersion of clay, which in turn can create adverse chemical (decreased availability of Ca^{2+} and Mg^{2+}) and physical (reduction in water infiltration rate and loss of favourable soil structure) problems for plant growth.

Use of resins to study the uptake of exchangeable cations was investigated in wheat and oats (Ratner, 1935), in Rhodes and Dallis grasses (Bower and Wadleigh, 1948) and in barley (Elgabaly, 1955). Following the development of soil conditioners it became possible to maintain favourable structure in soil containing large amounts of exchangeable sodium. Such studies have been conducted on oats, rice and wheat (Pearson and Bernstein, 1958), sweet corn (Allison, 1952), beans and clover (Bernstein and Pearson, 1956), barley (Pearson and Bernstein, 1958; Carr and Greenland, 1975), red beets, avacado, orange and carrots (Martin and Jones, 1954), ryegrass and tomatoes (Carr and Greenland, 1975), cotton (Chang and Dregne, 1955) and alfalfa (Chang and Dregne, 1955; Bernstein and Pearson, 1956).

Soil crusts affect the water regime through modification of infiltration, evaporation and redistribution, while crusts also prevent or retard seedling emergence (Rawitz and Hazan, 1978), as is the case in large areas of cultivated soil (Holder and Brown; 1974). As stated earlier, adding soil conditioners has produced measurable changes in the physical properties of several soils (Martin *et al.*, 1952). For tomato, sweet corn, rye grass and cotton application of polymers resulted in faster and better emergence. Plants grew visually 2 to 3 times taller, looked healthier and showed increased yield in treated soil (Allison, 1952; Cook and Nelson, 1986; Helalia and Letey, 1989). For wheat and tomato plants grown in non sodic soil, with a hard crust, the vegetative yields of both crops was greatly improved by polymer treatment (Wallace *et al.*, 1986). In the presence of sodicity increase in yield is due to the improved emergence due to greater structural stability of the polymer-treated soil (Carr and Greenland, 1975). It has been suggested that in sodic soils it is not the sodium that is inhibiting plants, but it is the soil structure (Allison, 1952).

2.3.5.2 Effects of polymers on ion uptake

There are very few reports of how application of polymers influences ion uptake under sodic conditions.

In sodic soils the effects of soil conditioners on uptake of ions by plants depend on plant species. Soil conditioners had little or no effect on uptake of Na^+, Ca^{2+} and K^+ by lettuce and cotton plants (Chang and Dregne, 1955). However, in peach (Martin and Jones, 1954) and alfalfa (Chang and Dregne, 1955) they resulted in lower Na^+ and higher Ca^{2+}, K^+, Mg^{2+}, N and P.

A search of the literature has revealed only one report of ion uptake by wheat plants grown in sodic conditions in the presence and absence of soil conditioner (Pearson and Bernstein, 1958). However, due to differences in ESP levels between the soil treated and un- treated with soil conditioner, this report is not clear.

2.3.5.3 Effect of polymers on crop yield

1953). There are also some reports of the effects of soil conditioners on the yield of different crops in sodic soils. At equal ESP levels (3, 18, 36, 45, 51) the yields of wheat, barley, oats and rice were greater in the presence of a soil conditioner than in its absence (Pearson and Bernstein, 1958). Green beans, table beets, clover and alfalfa have also shown greater yield at ESP levels of 35, 40 and in some cases 60 in the presence of soil conditioner than in its absence (Bernstein and Pearson, 1956). Carr and Greenland (1975) have also concluded that the yield of ryegrass, tomatoes and barley in sodic soil with high sodicity levels were significantly greater in the presence of soil conditioners than in its absence. The threshold level of sodicity damage can also be increased by soil conditioners. For example: reduction in alfalfa yield occurred at between ESP 29 and 39 in un-conditioned soil and between 39 and 45 ESP in conditioned soils (Chang and Dregne, 1955). At low sodicity levels soil conditioners have no or a slight inhibiting effect on crop yields (Bernstein and Pearson, 1956; Pearson and Bernstein, 1958).

It is evident from this literature review that sodicity is a global (Section 2) problem. It decreases growth (Sections 2.2.2.2 and 2.2.5.2) and yield (Section 2.2.6.2) of several crops including wheat, by inhibiting emergence (Section 2.2.1.2) and affecting ion uptake (Sections 2.2.3.2 and 2.2.4.2). It also seems to be evident that some crops including wheat are most sensitive at emergence than at later stages (Section 2.2.1.2). Different crop species (Section 2.2.6.2) and genotypes either tolerant or sensitive respond differentially to saline and or sodic conditions. There are some reports (Table 2.2 and Section 2.2.3.5) about the individual effects of poor soil structure and sodium toxicity in sodic soils. Synthetic organic polymers, especially anionic PAM, have been shown to be most effective for improving the structure of soils.

In the light of this, three research themes have been developed in this thesis:

1) Attempts to quantify the separate effects of high ESP and poor soil structure as causes of the lower yield of wheat in sodic soils;
2) Attempts to improve the performance of wheat in sodic soils by using novel sowing method;
3) The attempts to evaluate the usefulness of a genetic character that enables wheat to discriminate between Na^+ and K^+.

The experiments performed are reported in the following chapters:

5, 6, 7, 8, 9 and 10

CHAPTER 3

Soil preparation, general analytical procedures and varieties used in this study

CHAPTER 3

Soil preparation, general analytical procedures and varieties used in this study

3.1 Preparation of saline and sodic soils

3.1.1 Preparation of sodic soils

Sodic soils were prepared following the method described by Bains and Fireman (1964). The soils collected from the field were air dried, by spreading on the floor of a glasshouse. Air dried soils were then passed through a 3 mm sieve. The required amount of the appropriate soil was spread on a polyethylene sheet as a thin (1-2 cm) layer. To generate low ESP level, 0.25M $NaHCO_3$ solution was sprayed @ 160 ml/kg soil. A few minutes later another thin layer of soil was uniformly spread over the first treated soil layer, it was also sprayed with the same volume and concentration of salt solution using a knapsack sprayer.

To generate medium, high and very high ESP levels, equal amounts of other soil lots were treated with 0.5M, 0.75M and 1M $NaHCO_3$, using the same volumes and method as in the low ESP level. The treated soil lots were covered with other polyethylene sheets to reduce evaporation and to give maximum time for the soil to react with the sodium solution. The covers were then removed 3 days later. On the 4th day the soil of each lot was then mixed and raked and was allowed to air dry on the floor of the glasshouse.

3.1.2 Polymer (PAM) application

After the sodic soils had been prepared, half of the soil of each treatment was treated by spraying the soil with an anionic Polycrylamide (PAM) solution @ 0.2kg /100kg of soil using a knapsack sprayer. The PAM (Soiltex L1 soil conditioner) was supplied by Allied Colloids Limited, P. O. Box 38, Bradford, West Yorkshire BD12 0JZ, England. Aqueous solution was prepared by adding the calculated volume of concentrated (200g per kg anionic polyacrylamide in aqueous solution) polymer liquid to distilled water with vigorous stirring. The amount of water applied was sufficient to wet the soil. Before filling the pots, the PAM treated soil was allowed to air dry in a glasshouse. Much care was taken while filling the pots to produce as little physical disturbance as possible.

3.1.3 Preparation of saline soils

To calculate the salt treatment required for 1 kg of air dry soil, the method described by Rowell (1994) was used in the saline soil treatments of three experiments (2, 10 and 11):

For example the saturation percentage and the water content of the soil used in Experiments 10 and 11 were 47.5 g H_2O /100 g oven-dry soil and 3.6 g H_2O /100 g air dry-soil respectively. Hence 1kg of air dry soil had 36.8g of water and 963.2g of oven-dried soil. Thus the saturated paste of this soil contained:

47.5 x 963.2/100 = 457.52 g H_2O

To obtain 120, 150 and 180 mmol_c salt l^{-1}, the amounts of salt added to this soil were calculated as follows:

(1) 120 x 457.52/1000 = 54.90 mmol_c salt kg^{-1} air dry soil.

(2) 150 x 457.52/1000 = 68.62 mmol_c salt kg^{-1} air dry soil.

(3) 180 x 457.52/1000 = 82.35 mmol_c salt kg^{-1} air dry soil

Choice of salts

Na^+, Ca^{2+}, Mg^{2+} and Cl^- have been reported as the predominant ions in the saline soils of Pakistan especially in Sindh region, hence a mixture of NaCl, $CaCl_2$ and $MgCl_2$ salts with equal amounts of Na^+, Ca^{2+} and Mg^{2+} (mmol_c l^{-1}) was used in this study. The following table shows the amounts of salts calculated for 1 kg soil.

Total amount of salt required (120 mmol_c kg^{-1} air dry soil)

	Na^+	Ca^{2+}	Mg^{2+}
(mmol_c kg^{-1})	18.3	18.3	18.3
(mmol kg^{-1})	18.3	9.15	9.15
Salt	NaCl	$CaCl_2.2H_2O$	$MgCl_2$
Molar mass (g mol^{-1})	58.44	147.02	95.22
Mass of salt required (g kg^{-1})	1.07	1.33	0.87

The amount of salt required for 150 and 180 mmol$_c$ l^{-1} was calculated following the same method as for 120 mmol$_c$ kg^{-1}.

EC$_e$, Na$^+$, Ca^{2+} and Mg^{2+} were determined on a saturated paste extract (see below). The following equations (Rowell, 1994) were used to calculate SAR and ESP from the values of Na$^+$, Ca^{2+} and Mg^{2+}:

$SAR = [Na^+]/ [(Ca^{2+} + Mg^{2+})]^{1/2}$

Where, [ ] = represents the concentration in mmoll^{-1} (note; the unit is important).

For calculating ESP, first ESR was calculated as:

$ESR = -0.013 + 0.015\ SAR$ (Rowell, 1994)

The ESP was calculated from ESR using the following equation:

$ESP = 100\ ESR / (1 + ESR)$

Where ESP = Exchangeable Sodium Percentage

ESR = Exchangeable Sodium Ratio and

SAR = Sodium Adsorption Ratio.

3.2 Methods used for soil and plant analyses

Most of the soil chemical and physical properties, except the % of water stable aggregates, and the plant analyses were determined and analysed using standard procedures. These are listed below:

Analysis	**Method**
(A. Soil) Texture	Bouyoucos hydrometer method. Practical Agricultural Chemistry, Knawar & Chopra (1950) Method no. 2:12, pp 48. X-ray method for silt and clay analysis. Using Sedigraph 5000ET particle size analyser. Micromertics Instrument Corporation, Sales and Service Department, 5680 Goshen Springs Road Norcross, Georgia 30093, USA.
Saturation extract	Saturated paste method **(1)** Soil Sampling & Methods of Analysis, Rhoades (1982) pp. 162-165. (M. R. Carter, Eds.), Canadian Society of Soil Science.© 193 Lewish Publishers. **(2)** Soil Science Methods & Applications Section 14.2, D. L. Rowell. Eddison Wesley Longman Ltd. Edinburgh Gate, Harlow, Essex, CM20 2JE, England.

EC_e (dSm^{-1})	This was recorded on a saturation extract using a portable, digital EC meter (Mettler Toledo Analytical AG, Sonnenvergstrasse-74. CH-8603. Schwerzenbach Switzerland, made in USA). Method no. 4. Diagnosis and improvement of saline and alkaline soils. Agriculture Hand Book 60, 1954
pH	Soil pH was recorded using 1:2.5 soil water extract with portable digital pH meter. Method no. 32, page 98, The Analysis of Agricultural Materials, Ministry of Agriculture Fisheries & Food, 3rd Eds. (1985). London Her Majesty's Stationery Office.
Soluble Na^+, K^+, Ca^{2+} and Mg^{2+}	Concentration of these cations in saturation extract were determined by atomic absorption spectrophtometery.151aa/a Spectrophtometer. Instrumentation Laboratories, Lexington, Mass 02173.
C and N %	C and N % were analysed by an automated combustion method using LECO®CHN-2000 analyser, LECO® Corp. Lakeview Avenue, St. Joseph M1, 49085-2396, USA. Approximately 0.2g soil samples were weighed in a tin foil (LECO # 502-092). The samples were then introduced into the combustion chamber set at 1000 °C. The output was collected from the printer connected to the micro-computer of the analyser.

(B) Plant analysis

Leaf area	Leaf area was determined by an automatic leaf area meter (model AAM-7, Hayashi Denkoh Co, Tokyo, Japan).
Leaf sap extraction	Cell sap was extracted by crushing frozen leaf tissues in an Eppendorf tube, using a metal rod. After making hole in the base, the eppendorf tube (with crushed tissues) was placed in another opened top empty Eppendorf tube. Sample was then centrifuged at 8555 rpm and sap was collected in the second tube (Gorham *et al.*, 1997).
Leaf sap analysis for Na^+ K^+, Ca^{2+} and Mg^{2+}	These ions were determined by atomic absorption spectrophotometery.151aa/ae Spectrophotometer. Instrumentation Lab. Lexington, Mass 02173.

Cl$^-$ in leaf sap	This was determined by Cl$^-$ electrode, using Microprocessor Ionalzer/901. Orion Research Incorporated. 380 Putman Avenue, Cambrige.
Preparation of grain & straw samples for ion analysis	These samples were oven dried, ground and ashed at 450 ^{0}C in a muffle furnace. The ash was then digested in acid (5M HCl) and filtered through Whatman no.42 (filter paper). Filtrate was stored for chemical analysis. Method no. 3, page no. 8. The Analysis of Agricultural Materials, Ministry of Agriculture Fisheries & Food, 3rd Eds. (1985). London Her Majesty's Stationery Office.
Analysis of Na^+, K^+, Ca^{2+}, Mg^{2+} and micronutrients in the filtrate prepared from grain and straw samples	This was done by Plasma atomic emission spectrometery, using an ICP AES and Elemental analyser (Inductive Coupled Plasma Atomic Emission Spectrometer). JY (Jobin Yvon), Emission Instruments, S.A. (UK) Ltd., 2-4, Wigton Gardens, Stemmore, Middlesex HA7, 1BG, UK.
Wave lengths (nm) of different elements used in ICP analysis	Zn^{2+} = 213.86, Mn^{2+} = 257.61, Fe^{2+} = 259.94, Cu^{2+} = 324.75, Ca^{2+} =317.93, Mg^{2+}= 279.55, Na^+ = 589.59 K^+ = 766.5
Grain & straw N (%)	This was determined on ground grain and straw samples by an automated combustion method, using LECO® CHN-2000 analyser, LECO® Corp. Lakeview Avenue, St. Joseph M1, 49085-2396, USA. In this method approximately 0.2g of plant tissue were weighed in a tin foil (LECO # 502-092). The samples were then introduced into the combustion chamber set at 1000 °C. The output was collected from the printer connected to the micro-computer of the analyser.

3.3 Measurement of water stable aggregates percentage (%)

Aggregate stability was determined by measuring the proportion of aggregates of 2 to 5 mm size following the wet sieving method described by Angers and Mehuys, (1993).

Materials, equipment and reagents used to measure WSA %

1, A wet-sieving apparatus with 250 µm sieve;

2, Erlenmeyer flasks with 250 ml capacity;

3, $(NaPO_3)_6$ (0.5 % w/v) dispersing solution.

Procedure

2 to 5 mm air-dried soil aggregates (10 g (w1)) were spread on a 250 µm sieve of the wet sieving apparatus. The sieve was then lowered to a water surface and the aggregates were allowed to be wet by capillarity for 10 minutes. The height of the sieve was adjusted so that all the aggregates remained immersed in water on the upstroke of the machine. The motor was then started and the sieve was allowed to be raised and lowered 3.7 cm, 20 times / min for 30 minutes. After 30 minutes the sieve was removed and the stable aggregates were washed into a tared 250 ml Erlenmeyer flask. The aggregates were oven dried at 105 °C and their dry weight (w2) was recorded. Approximately 50 ml of 0.5 % $(NaPO_3)_6$ was added to the flask, which was then shaken for 45 minutes using an electrical shaker. The dispersed aggregates were washed through the 250 µm sieve. After washing the dispersed aggregates the remaining primary particles (mineral matter) on the sieve were again collected into the same flask and were oven dried at 105 °C to record their dry weight (w3).

A sub-sample of 2 to 5 mm sized aggregates was taken to measure the gravimetric water content (wc), following the method described below:
10 grams of air-dried soil taken in a crucible was placed in an oven at 105 °C overnight. After cooling in a desiccator, the weight of sample was again recorded.

Example

Mass of air-dry soil = 10g

Mass of oven-dry soil = 9.81g

Mass of water lost = 0.19g

Water content = 0.19/9.81 = 0.019 g of H_2O/ g of oven-dry soil.

% of gravimetric water content = 1.9 % (1.9 g of water per 100g of oven-dry soil)

Calculations for water stable aggregates percentage

$\% \text{ WSA} = 100 (w2 - w3)/ ((w1/(1+wc))- w3)$

Where:

WSA = Water stable aggregates

w1 = 10g of 2-5mm air dried original soil aggregates

w2 = Oven dried weight of stable soil aggregates (after sieving)

w3 = Oven dried weight of mineral matter (after dispersing the stable aggregates)

wc = Gravimetric water

Note: Three types of soils were used in this study. For the clay loam soil (experiment 3) collected from Caeglanmore field and for the loamy sand soil (experiment 4) the time of soaking and sieving was used as stated in the above procedure. For the clay loam soil used in experiments 2, 5, 6, 7 and 8 the time of soaking was 5 minutes and the sieving time was 10 minutes.

3.4 List of varieties used in this study

Table 3.1 shows the list of varieties tested in this study. The varieties tested included hexaploid wheat varieties from Pakistan and most of them were known to differ in salt-tolerance. Some UK wheat varieties were also incorporated which were expected to be salt-sensitive. Four durum (tetraploid) wheat genotypes with and without Kna1 gene were also tested in this study.

Table 3.1. Hexaploid wheat varieties and tetraploid wheat genotypes tested in this study

Wheat	Variety/genotype	Salt-tolerant/susceptible	Source
Hexaploid wheat varieties			
	Anmol	Unknown	Wheat Research Institute Sakrand Sindh, Pakistan
	Avalon	Unknown	Winter wheat (PBI Cambridge)
	Bakhtwar	Unknown	Pakistan
	Cadenza	Unknown	Spring wheat (UK)
	Kharchia-65	Tolerant	Parkash & Sastry (1992)
	KRL 1-4	Tolerant	Pure breeding line (Kharchia-65 local x WL 711)
	KRL 1-3	Tolerant	Unknown
	KTDH-19	Resistant	Kharchia-65 x TW-161
	LU- 26S	Resistant	Blue silver x Khushal (selection)
	Mehran 89	Unknown	Wheat research Institute, Sakrand Sindh, Pakistan
	NIAB-20	Tolerant	LU-26S x *A. cylindrica*
	PAK-81	Salt-sensitive	Cultivated (Pakistani) Farooq *et al.*(1994)
	Pasban	Unknown	Cultivated wheat (Pakistan) Farooq *et al.* (1994)
	Q-19	Unknown	Unknown
	SARC-1	Tolerant	Selection from LU-26S
	SARC-111	Tolerant to alkalinity	Selection from Lyallpur 73
	T. J-83	Unknown	Wheat Research Institute Tando Jam, Sindh, Pakistan
	Tonic	Unknown	UK Spring wheat
	TW-161	Unknown	Unknown
Tetraploid (Durum) wheat genotypes			
	R112$^+$	Tolerant (+ Knal)	Dvorak *et al.* (1994)
	R173$^+$	Tolerant (+ Knal)	
	R21$^-$	Susceptible (- Knal)	
	R23$^-$	Susceptible (- Knal)	

CHAPTER 4

Selection of wheat varieties that can discriminate between K^+ and Na^+ under 120 mol m^{-3} hydroponic salinity

CHAPTER 4

Selection of wheat varieties that can discriminate between K^+ and Na^+ under 120 mol m^{-3} hydroponic salinity

4.1 Introduction

Although the addition of NaCl to the growth medium leads to a decrease in the accumulation of K^+, and an increase in the accumulation of Na^+ and Cl^- in cell sap, different species and varieties accumulate different amounts (Baykal, 1983). Some plants accumulate more Na^+ and Cl^- and less K^+, while others show the opposite trend of less Na^+ and Cl^- but more K^+. Similarly in wheat plants there have been various reports (Section 2.2.3.1) which show that in the presence of an equal salinity, some wheat species and varieties accumulate less K^+ but more Na^+ and Cl^- in their leaves, hence they show lower K^+/Na^+ ratio, while other wheat species and varieties accumulate less Na^+ and Cl^- but more K^+, thus they show high K^+/Na^+ ratio (Ashraf and O'Leary, 1996).

It has been considered by several workers that the discrimination between plants in Na^+ and K^+ accumulation determines the ability of plants to respond under saline conditions as salt-resistant or sensitive. Hence the use of K^+/Na^+ ratio as one of the criteria for selecting salt tolerant and salt-sensitive plants including wheat has been adopted by several workers (Greenway and Munns, 1980; Parkash and Sastry, 1992).

It is not just salinity that decreases crop yield but soil sodicity also exists on a large scale in the world of agriculture (Table 2.1 and Section 2.1.1). The conditions of soil sodicity cannot be identical to that of soil salinity, hence the plants resistant to salinity stress, may or may not be resistant to the stress of soil sodicity. Also, the response of varieties under hydroponic culture may or may not be the same in soil culture. Varieties which are able to exclude Na^+ under saline conditions may also be useful under sodic condition, where ESP is higher. The recommendations of wheat varieties as resistant to both soil salinity and sodicity may provide the best possible opportunity to farmers for achieving the highest returns from both types of salt-affected fields. This comparative study was therefore started in the beginning of the research so that some suitable (salt-tolerant and susceptible) wheat varieties could be selected for further experiments comparing the effects of salinity and sodicity. These are reported in Chapters 5 and 7.

Generally Pakistani or Indian (sensitive or tolerant) varieties which are reported as salt-resistant or tolerant by earlier workers were incorporated in this experiment. Some UK wheat varieties, which were thought to be sensitive (Cadenza and Tonic) were also used in this experiment (Table 3.1). Ion concentrations were measured in two different leaves (fifth and flag leaves), as the flag leaf is an important source of carbohydrate for grain filling (Thorne, 1965).

4.2 Objectives

This experiment was started with the following specific objectives:

(1). To identify wheat varieties which can discriminate between K^+ and Na^+;

(2). To select salt resistant and susceptible wheat varieties for use in further experiments.

4.3 Materials and methods

4.3.1 Preparation of pots

Four pots (52x35 surface x15 cm depth) with 4 (7 mm holes, two in the front, one in the right side and one in the left side) holes for air supply and one hole (9 mm hole in front of each pot) for solution change were used in this experiment. Rubber bungs were used (No: 16: Terumo Europe, Belgium) to plug the holes for facilitating both the easy change of nutrient solutions and to fix air supply needles. Silicon tubing (Scientific Service, Chester, UK) which automatically seals the holes made by needles was used. All pots were placed on a trolley standing in a growth room. A silicon tube with 5 mm internal diameter and 8 mm external diameter was fixed along the trolley and was connected to the air regulator. Narrow Polyethylene capillary tubes (0.58 mm internal diameter and 0.96 mm external diameter) were used to supply air from silicon tubes to the pots. The capillary tubes were cut into appropriate lengths and then fixed with needles at both ends, one end inserted into the silicon tube and the other end into the bung fitted into the pots.

4.3.2 Raising and transplanting of seedlings

The experiment tested ten hexaploid wheat varieties (Tonic, LU-26S, Q-19, SARC-1, PAK- 81, KTDH-19, Cadenza, KRL1-4, Kharchia-65 and NIAB-20) (Table 3.1, Chapter 3). Seeds of all wheat varieties were pre-germinated in perlite using black painted plastic pots (10cm x 10cm surface x 16 cm deep).

Ten days after sowing, seedlings of each variety were transferred into the solution culture pots (52 cm x 23 cm surface x 16 cm deep). There were 4 pots and each pot was considered as a replication. In total, seven seedlings of each variety per pot were transferred. The seedlings were fixed in plastic lids (Plantpak trays, Maldon, UK) at a distance of 7 cm plant to plant and 6.0 cm row to row, using a completely randomised block design. A foam collar around the stem base of individual seedlings was used to hold the plants with their roots immersed in 25 litres aerated nutrient solution.

4.3.3 Growth conditions

The seedlings were raised and the experiment was performed in a walk-in growth chamber (set at 18 ^{0}C day and 9 ^{0}C night temperature, 65 % RH with photoperiod of 16 hours), at Henfaes Agricultural Research Station, University of Wales, Bangor, UK.

4.3.4 Salt stress and fertiliser

Salt stress of 120 mol m^{-3} NaCl and 6 mol m^{-3} of $CaCl_2$. H_2O was commenced seven days after transplanting (December 19, 1996) the seedlings. Salt-stress was introduced in three equal increments over a period of 5 days.

Phostrogen fertiliser (Phostrogen LTD, Deeside Industrial Park, Deeside, Flint Shire CH5 2NS) was applied to each pot @ 0.5 g/l of solution. In addition the Long Ashton Nutrient Solution to supply micro-nutrients (Hewitt, 1966) was also applied to each pot. The solution in the pots was initially changed after 10 days and later after every fifth day.

Composition of Phostrogen fertiliser

Nitrogen		**Phosphorus**	**Potassium**
Ammoniacal N	3.5%	10 % P_2O_5 soluble in water (4.4 % P)	$K_2O = 27\%$
Ureic N	2.5%	10 % P_2O_5 insoluble in water (4.4 % P)	
Nitric N	8.0%		
Total N	14%		

Micronutrients & other ions

MgO = Soluble in water 2.5 %, (Mg 1.5%).
SO_3 = Soluble in water 11.00 % (S 4.4%).
Boron = Soluble in water 0.01 %.
CaO = Soluble in water 1.0% (Ca 0.71%).

Cu^{2+} EDTA = 0.004%
Mn^{2+} EDTA = 0.0210%
Zn^{2+} EDTA = 0.004%
Fe^{2+} EDTA = 0.0400%
Mo = 0.0016%

Composition of Long Ashton Nutrient solution

Four stock solutions were prepared and from these the amounts specified were taken and added to the nutrient solution.

	Stock solution g l^{-1}		***Volume of stock solution (ml) for one litre of nutrient solution***
$MnSO_4.4H_2O$ =	22.3	=	0.1
$CuSO_4.5H_2O$ =	2.5		
$ZnSO_4.7H_2O$ =	2.9		
Fe EDTA	37.3	=	0.5
H_3BO_3	31.0	=	0.1
$Na_2MoO_4.H_2O$	1.2	=	0.1

4.3.5 Harvesting and measurements

Three plants per variety per replication were harvested 32 days after transplanting when the 5th leaf on the main stem became fully expanded. The remaining 4 plants per variety per replication were harvested when the flag leaf became fully expanded. The flag leaf stage of different varieties was achieved on different dates (Table 4.1). At each harvest the number of fully expanded leaves on the main stem, number of tillers per plant and shoot height (from base of the plant to the tip of the longest leaf) were noted. Shoot dry weight of plants at both harvests was also recorded after oven drying the green plant matter at 80 °C for two days.

4.3.6 Leaf sampling, sap extraction and chemical analysis

The fifth leaf of three plants at the first harvest and the flag leaf of four plants at the second harvest were detached, placed in Eppendorf tubes and stored in a freezer set at -10 °C. The lamina of the fifth and flag leaf were removed and the sap was extracted and analysed for Na^+, K^+, and Cl^- following the procedures described in Section 3.2 (Chapter 3).

4.3.7 Statistical analysis

All data were analysed by the analysis of variance (ANOVA) method, using one way ANOVA in Minitab statistical package, version 10.51. Linear correlation analysis between ion uptake and growth parameters was performed using SPSS statistical package, version 8. Significance levels are shown in the tables by *, **, *** for 5%, 1% and 0.1% probability levels, respectively. The non significant differences are denoted by N. S. The standard error of the differences between means (S. E. D.) and the least significant differences (L. S. D.) were calculated, using the following formulae:

S. E. D. = $\sqrt{2EMS / n}$

L. S. D. = S. E. D x t (0.05) df

where EMS = error mean square;

n = number of replicates;

t (0.05) df = value from the t distribution table at 5 % probability level and error degrees of freedom.

4.4 Results

4.4.1 Growth and development

There were significant differences between the varieties in all the growth and development variables measured at both harvests (Table 4.1). The differences between varieties in most of the variables recorded at both harvests were not consistent. Q-19 showed poor performance at both harvests with shorter plants, no tillers and lower shoot dry weight than all other varieties. With the exception of number of tillers and leaves, Kharchia-65 showed taller plants at both harvests and higher shoot dry weight at first harvest. At the second harvest KTDH-19 and Cadenza were the second tallest varieties,

Table 4.1. Varietal effects on the growth and development of wheat grown under hydroponic salinity

	First harvest					Second harvest			
Varieties	Height (cm)	No. leaves on the main stem/plant	No. tillers/ plant	Dry wt (mg/plant)	Flag leaf expanded at (DAT)	Height (cm)	No. leaves on the main stem/plant	No. tillers/ plant	Dry wt (mg/plant)
Tonic	41	5.8	0.24	277	53	55	7.8	1.10	692
LU-26S	40	6.4	0.60	431	46	57	8.5	0.63	619
Q-19	29	6.0	0.00	178	43	33	7.3	0.00	249
KRL, 1-4	40	5.9	0.00	287	43	53	6.8	0.00	466
Kharchia-65	58	6.0	0.32	569	39	72	7.2	1.13	777
SARC-1	36	6.8	0.10	299	43	46	7.7	0.30	413
PAK-81	39	6.0	0.50	293	53	50	8.5	1.13	592
KTDH-19	38	5.8	0.70	272	61	61	8.7	3.00	944
Cadenza	40	5.9	0.83	304	61	64	8.4	2.00	856
NIAB-20	40	6.1	0.70	525	43	52	7.8	1.00	685
S. E. D.	1.0	0.22	0.19	55.0		2.2	0.16	0.27	108.0
L. S. D.	2.9* * *	0.45* * *	0.16*	113.0* * *		6.4* * *	0.48* * *	0.79* * *	220.0* * *

they had considerably more leaves, more tillers and higher shoot dry weight than all other varieties tested. The other varieties tested in this experiment remained intermediate. The number of days after transplanting at which the flag leaf fully expanded stage was reached varied from 39 to 61. Some varieties (Q-19, SARC-1, NIAB-20, and) generally took fewer days and some (KTDH-19 and Cadenza) took many more days to expand their flag leaves than others.

4.4.2 Ion concentrations

Table 4.2 shows the ion concentrations and K^+/Na^+ ratio in leaf five and the flag leaf of ten wheat varieties. Significant differences were found between the varieties in Na^+, Cl^- and K^+/Na^+ ratio in both leaves. Significant differences between varieties in K^+ were only noted in flag leaf sap.

Differences between varieties in ion uptake were not consistent in the two leaves (5th and flag leaf). For example, Q19 showed high Na^+ in both leaves. Tonic, LU-26S and PAK-81 showed moderately higher Na^+ in both leaves. Cadenza and Kharchia-65 showed higher Na^+ in leaf five but lower in the flag leaf. Contrarily SARC-1 showed an opposite trend viz, lower Na^+ in leaf 5 and higher Na^+ in flag leaf. In other varieties (KTDH-19, NIAB-20 and KRL1-4) there was no marked difference between the values of Na^+ concentration in leaf five and the flag leaf.

Although it was only statistically significant in the flag leaf sap, different varieties showed different values of K^+. Also the concentration of K^+ in the same variety was inconsistent in both leaves. Some varieties (LU-26S) showed lower K^+ in leaf five but higher K^+ in flag leaf. With the exception of LU-26S, which showed an opposite trend, almost all varieties tested showed higher K^+ in leaf five and lower K^+ in the flag leaf.

The concentration of Cl^- in both leaves was greater than Na^+. Although all varieties were grown at the same salinity level (120 mol m^{-3}), they accumulated significantly different amounts of Cl^- in their leaves. In almost all cases the amount of Cl^- ion was different between leaves. In the different varieties Cl^- concentration was markedly (Q-19, KRL1-4, KTDH-19 and Kharchia-65), moderately (LU-26S, Tonic, PAK-81 and Cadenza) and slightly (NIAB-20) lower in the flag leaf than in the fifth leaf. In both leaves Q-19 and Cadenza had high Cl^-. Q-19 showed lower K^+/Na^+ ratio in both leaves than other varieties. Similarly as with other ions, K^+/Na^+ ratio was not consistent between the leaves. Some varieties (NIAB-20, KTDH-19, PAK-81, SARC-1 and Tonic) showed high K^+/Na^+ ratio in leaf five but a lower K^+/Na^+ ratio in the flag leaf, while others (Kharchia-65, LU-26S) showed an opposite trend i.e., lower K^+/Na^+ ratio in fifth but higher in flag leaf. Other varieties (Cadenza and KRL1-4) did not show a difference between the leaves for K^+/Na^+.

Table 4.2. Na^+, K^+, and Cl^- concentrations and K^+/Na^+ ratio in the sap of fifth and flag leaf of ten wheat varieties, grown under hydroponic culture salinity (120 mol m^{-3} NaCl + 6 mol m^{-3} of $CaCl_2$).

Varieties	Fifth leaf				Flag Leaf			
	Na^+	K^+	K^+/Na^+	Cl^-	Na^+	K^+	K^+/Na^+	Cl^-
	mol m^{-3}				mol m^{-3}			
Tonic	64	229	3.6	323	76	150	2.0	243
LU-26S	65	215	3.4	273	71	378	4.6	144
Q-19	85	228	2.7	433	144	211	1.5	214
KRL, 1-4	54	225	4.4	370	40	179	4.7	171
Kharchia-65	79	244	3.2	286	19	152	8.2	170
SARC-1	43	225	5.6	291	72	176	2.5	251
PAK-81	62	220	3.6	377	78	179	2.5	244
KTDH-19	44	243	5.8	438	40	74	2.5	200
Cadenza	84	242	2.7	471	42	126	3.1	385
NIAB-20	51	226	4.4	285	41	75	2.0	253
S. E. D.	7.2	18.0	0.66	25.0	8.0	27.0	0.60	20.0
L. S. D.	15.0***	N. S	1.35***	50.0***	15.0***	56.0***	1.19***	43.0***

4.4.3 Relationship between ion uptake and shoot dry weight

There was no significant correlation between shoot dry weight and uptake of Na^+, K^+ and K^+/Na^+ ratio at the first harvest, but Cl^- showed a significant negative correlation with shoot dry weight (Table 4.3) although the r value was small. At the second harvest both Na^+ and K^+ were significantly negatively correlated with shoot dry weight, and there was no significant correlation between shoot dry weight and Cl^- and K^+/Na^+ ratio.

Table 4.3 Linear correlation coefficients between leaf Na^+, K^+, Cl^- concentrations, K^+/Na^+ ratio and shoot dry weight of plants at two harvests

Harvest	Ions			
	Na^+	K^+	K^+/Na^+	Cl^-
5th leaf (first harvest)	0.090 NS	0.066 NS	0.043 NS	- 0.333*
Flag leaf (Second harvest)	- 0.595* *	- 0.415* *	0.156 NS	0.153 NS

4.5 Discussion

The results obtained from this study provided evidence that at both harvests out of ten varieties tested, Q-19 showed poor performance in terms of growth and development under saline conditions while the response of three varieties viz. KTDH-19, Cadenza and Kharchia-65 was considerably better than that of the other six varieties which was intermediate (Table 4.1).

The poor performance of Q-19 was clearly associated with higher flag leaf Na^+ and lower K^+/Na^+ ratio and the better performance of Kharchia-65 was associated with lower flag leaf Na^+ and Cl^- and higher K^+/Na^+ ratio. There have been several reports (Section 6.1) showing that Kharchia-65 is a salt-tolerant variety. Although the growth (height, seedling dry weight and number of tillers) of KTDH-19 and Cadenza was higher compared to other varieties, the ion concentrations did not show a clear association with this, because the concentrations of Na^+ and Cl^- were not markedly different from those of some other varieties which showed intermediate growth. This suggests that possibly when these two varieties achieved the flag leaf stage they were still growing, so that they had taller plants and more shoot dry weight. The significant negative correlation of Cl^- ions but not other ions with shoot dry weight at the first harvest indicates the greater toxic effect of Cl^- than Na^+. At the second harvest the effect of Na^+ seemed to be greater than Cl^-. K^+/Na^+ did not show a significant correlation at both harvests. It was interesting to notice that K^+ had a negative significance correlation at the second harvest. This was due to the fact that varieties which showed poor growth and development (Q-19) did not show lower K^+ than those which showed good performance. These results suggest that K^+/Na^+ ratio should not be considered as the only criteria for salt-tolerance, but the concentrations of Cl^- and Na^+ and more important growth and development must be taken into account while selecting wheat varieties. There were differences between the leaves in ion concentrations. Although it depends upon variety, Cl^-, K^+ and to some extent K^+/Na^+ were generally higher in the leaf five than in the flag leaf, whereas Na^+ remained higher in the flag leaf than the fifth leaf. This suggests that varieties may or may not show consistent trends at all growth stages, so that for a wise selection a proper and reliable stage should be used.

On the basis of overall performance, especially K^+/Na^+ ratio, Q-19 as a salt-susceptible and Kharchia-65 as a salt-tolerant variety were selected as qualified candidates for further experimentation. In addition to Q-19 and Kharchia-65, other varieties were also tested in various experiments conducted for this study.

CHAPTER 5

Physico-chemical effects of sodic soils on emergence, ion uptake and growth of wheat seedlings

CHAPTER 5

Physico-chemical effects of sodic soils on emergence, ion uptake and growth of wheat seedlings

5.1 Introduction

It is considered by many workers (Mustafa *et al.*, 1966; Barzegar *et al.*, 1997) that poor soil structure and sodium toxicity are the main adverse physico-chemical features of sodic soils. These limit seedling emergence, growth of plants and increase the concentration of toxic ions in plants. The damage caused by sodicity depends on soil properties such as, organic matter, type and content of clay, extent of pH and ESP (Singh and Abrol, 1985; Rowell, 1994; Boem and Lavado, 1996).

The effects of sodicity on plants depend not only on soil characteristics, but also on plant characteristics (Boem and Lavado, 1996). Several workers (Mehotra and DAS, 1973; Gorham, *et al.*,1997) have shown that, among other factors, genetic variation, varietal differences and growth stage can influence the tolerance of wheat to sodicity.

Much of the experimental information published on the effects of sodicity on germination, growth and ion uptake of wheat relates to the effects of high ESP. Little research has been conducted to identify the separate effects of ESP and poor soil physical properties. Also, there have been no clear reports whether varieties tolerant of sodic conditions are tolerant of poor structure or excessive sodium or both. The reason for this is that the investigators did not pay sufficient attention to the separation of physical and chemical effects of sodic soil. Separation of adverse physical effects from chemical effects is difficult. As described in Chapter 1, treating soils with polymers (soil conditioners) is one possible means of accomplishing this separation (Allison, 1956).

Taking into consideration all that, the aim of the present study was to quantify the separate effects of adverse physical and chemical conditions in sodic soils. Three experiments were conducted for this study. In experiment 2 different varieties were compared for their seedling emergence and growth up to 20 DAS. Experiments 3 and 4 tested more varieties including several durum wheat genotypes, in two soils of contrasting texture. In experiment 2 there was only one salinity and one sodicity level with and without PAM, but in experiments 3 and 4 a series of sodicity levels (low, medium and high), with and without PAM, were used. Ion uptake by seedlings may vary with and without PAM or it may depend on variety and soil type. To investigate this, ion uptake was analysed in experiments 3 and 4.

5.2 Objectives

Three experiments were conducted with the following specific objectives:

(1). To separate out the physical and chemical effects of sodic soils, with different textures, on emergence, growth and ion uptake of wheat at an early seedling stage, using an anionic polyacrylamide soil conditioner (PAM);

(2). To identify sodicity-tolerant and susceptible hexaploid wheat varieties and durum wheat genotypes.

5.3 Experiment 2

Effects of high soil sodicity (with and without PAM) and high soil salinity on the seedling emergence and growth of different varieties under clay loam soil conditions

The main purpose of this experiment was to separate out the physical and chemical effects of sodicity (high ESP) on emergence and growth of different wheat varieties under clay loam soil conditions. The second purpose of this experiment was to determine if the effects of PAM varied between varieties. Varieties that perform well in sodic soil conditions may or may not perform well under saline soil conditions. To investigate this the varieties were also grown in a saline soil treatment. Soil salinity is not due only to increase in Na^+ and Cl^- ions but there may be higher concentrations of other ions (Ca^{2+}, SO_4^{2-} and Mg^{2+} etc). Thus in this study a mixture of different salts ($NaCl$, $CaCl_2.H_2O$ and $MgCl_2$ was added to prepare a saline soil.

5.3.1 Objectives

This experiment had the following objectives:

(1). To determine the effects of soil sodicity and salinity on seedling emergence and growth;

(2). To determine the extent to which it was possible to decrease the adverse effects of sodicity by improving soil structure with PAM;

(3). To identify varieties tolerant and sensitive to sodicity as well as salinity;

(4). To identify varietal differences in response to PAM.

The experiment tested four soil treatments: control soil, saline soil, sodic soil and sodic soil treated with PAM.

5.3.2 Materials and methods

5.3.2.1 Soil preparation

Soil (plough layer) was collected from a cultivated field on the research area of Henfaes Agricultural Research Station, Bangor, UK.

To establish an ESP of approximately 50, soil (120 kg) was sprayed with 1M $NaHCO_3$ (Section 3.1.1). To stabilise the structure of sodic soil in the presence of high exchangeable sodium, 60 kg of artificially alkalized sodic soil was treated with anionic polyacrylamide soil conditioner at the rate of 0.2 kg/100 kg of soil, using the method described in Chapter 3 (Section 3.1.2).

To prepare a saline soil treatment with an EC_e of approximately 18 (dSm^{-1}) a salt mixture was added as described in Chapter 3 (Section 3.1.3). The mixture of salts consisted of NaCl, $CaCl_2$ and $MgCl_2$. Each pot contained 30 kg soil. The saturation % and moisture content of this soil were 47 and 9.7 % respectively.

5.3.2.2 Growth conditions

This experiment was performed in a glasshouse during May 1997, at Henfaes Agricultural Research Station. The glasshouse was kept well ventilated and no supplementary heating or lighting was used. The temperature of the glasshouse during the study is shown in Appendix 1.

5.3.2.3 Seed sowing

There were two pots (52 cm x 23 cm surface x16 cm deep) of each soil treatment. Seeds of eleven wheat (*Triticum aestivum* L.) varieties (Kharchia-65, T. J-83, Mehran-89, Anmol, NIAB-20, PAK-81, TW-161, Bakhtwar, Pasban, KTDH-19 and

SARC-1) were sown in the pots on May 3, 1997. There were 8 rows (replicates) per pot. Each row contained the 11 varieties in a separate random order. Single seeds of each variety were placed in each position with 3 cm row to row and 4 cm seed to seed distance. Tap water was applied to each pot as needed. To apply sufficient plant nutrients, two litres of 0.5g Phostrogen fertiliser /l of soil (Section 4.3.4) were applied to each pot at the time of sowing.

5.3.2.4 Recording of seedling emergence and final harvest

To record emergence percentage, all emerged seedlings were counted in one pot ten and twenty days after sowing. In the other pot all germinated plants were harvested at 10 DAS by carefully uprooting. Shoot height and root length were measured. These plants were washed with tap water and oven dried at 82 °C for 48 hours and their dry weight was recorded.

5.3.2.5 Soil analyses

Before sowing and after harvesting of seedlings, soil samples were collected and analysed for chemical (Na^+, K^+, Ca^{2+}, Mg^{2+}, pH, EC_e, total N % and total C %) and physical properties (soil texture and water stable aggregates (WSA %). The methods used for determining chemical and physical analysis and calculations of SAR and ESP are published in "Soil Science Methods and Applications" (Rowell, 1994), Soil Sampling and Methods of Analysis (Rhoades, 1982) and adopted in the Soil Science Department, School of Agricultural and Forest Sciences, University of Wales, Bangor.

5.3.2.6 Statistical analyses

The data for three varieties (T. J-83, Mehran-89 and Pasban) were omitted due to low emergence in all treatments, including the control. The seedling emergence percentages data with 8 replicates at both stages were analysed by transforming the data into arcsine values. Due to uneven numbers of plants emerged, five plants of each variety per treatment were selected at random for determination of shoot height, root length and shoot dry weight. Preliminary analyses of the data showed that there were differences between varieties within each treatment. To test for variety x treatment interactions the data for control, saline, sodic and sodic plus PAM treatments were pooled and an analysis of variance was performed using the procedure for analysis of a series of experiments, recommended by Cochran and Cox (1957). S. E. D and L. S. D. values were calculated using the formulae given in Chapter 4 (Section 4.3.7). Significance levels are shown in the tables by *, * *, and * * * for 5, 1 and 0.1% probability levels, respectively. The non-significant differences are denoted by N. S.

5.3.3 Results

5.3.3.1 Soil characteristics.

Table 5.1 shows the properties of soil used in this experiment (before sowing and after harvest).

The chemical properties of the original soil before sowing and after harvesting of the seedlings showed a pH value typical of that a well managed agricultural soil in the UK and low values of EC_e, SAR, and ESP with 1.5% of total carbon and 0.14 % total N. However, when the same soil was treated with 1M $NaHCO_3$ salt, it showed an increase in pH together with markedly higher values of ESP and SAR. The EC_e (dSm^{-1}) of treated soil was also increased but to a smaller extent. The effects of PAM on pH, ESP and SAR were very slight. After harvesting of the seedlings there was no distinct change in pH, SAR and ESP compared to before sowing, but EC_e increased.

As sodicity increased the percentage of water stable aggregates (WSA%) decreased. Treatment of sodic soil with PAM resulted in a large increase in the %WSA, so that the value obtained was similar to that of the control.

Following the addition of the salt mixture, there was a marked change in the chemical properties of soil. The value of EC_e was typical of that highly saline soil, but the pH value was lower compared to that of the control and sodic soil treatments. Although the SAR and ESP of the saline soil were higher than in the control, they were lower than the values of a typical sodic soils. At the time of harvest the saline soil showed a decrease in pH and EC_e, but an increase in SAR and ESP.

Table 5.1. pH, electrical conductivity (EC_e), sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), % water stable aggregates (%WSA), total carbon and nitrogen (%) and texture of the soil before sowing and after harvest

Before sowing

Treatment	Salt added	pH (H_2O)	EC_e (dSm^{-1})	SAR	ESP
Control	No salt	6.5	1.6	1.0	0.1
Sodic	1M ($NaHCO_3$)	9.2	3.0	62.5	48.0
Sodic + PAM	1M ($NaHCO_3$)	8.8	3.5	57.4	45.9
Saline (NaCl, $CaCl_2$ and $MgCl_2$)		5.9	19.2	3.4	3.7

Total carbon % (control soil) = 1.5 % (before sowing) **CHN analyser**
Total nitrogen % (control soil) = 0.14 % (before sowing)

Texture (Sedigraph method)		**(Hydrometer method)**
Sand total	= 44.4%	= 42.2 %
2000-------630μm	= 13.8 %	= 18.7 %
630μm ------200μm	= 16.1 %	= 9.9 %
200μm--------63μm	= 14.5 %	= 13.6 %
Silt------------------------	= 34.5 %	= 37.8 %
Clay-----------------------	= 21.1%	= 20.0 %
Textural Class		
(UK classification)	= Clay loam soil	= Clay loam soil
(USDA classification)	= Loam soil	= Loam soil

After harvest

Treatment	$NaHCO_3$ added	pH	EC_e (dSm^{-1})	SAR	ESP	Water stable aggregates (%)
Control	No salt	6.5	3.6	1.3	0.0	71
Sodic	1M ($NaHCO_3$)	8.8	8.3	64.1	48.6	38
Sodic + PAM	1M ($NaHCO_3$)	8.5	6.7	58.2	46.2	73
Saline (NaCl, $CaCl_2$ and $MgCl_2$)		5.0	18.6	10.6	12.7	not measured

5.3.3.2 Effects on seedling emergence (%)

The effects of salt-affected soil on seedling emergence % (averaged over all varieties) at 10 and 20 DAS are presented in Figure 5.1. The final emergence % recorded at 20 DAS are shown in Table 5.1.1. Seedling emergence % was significantly lower in the salt-affected soil treatments than the control. The effect of salinity was significantly greater than that of sodicity. The effect of salinity was to decrease the emergence %.

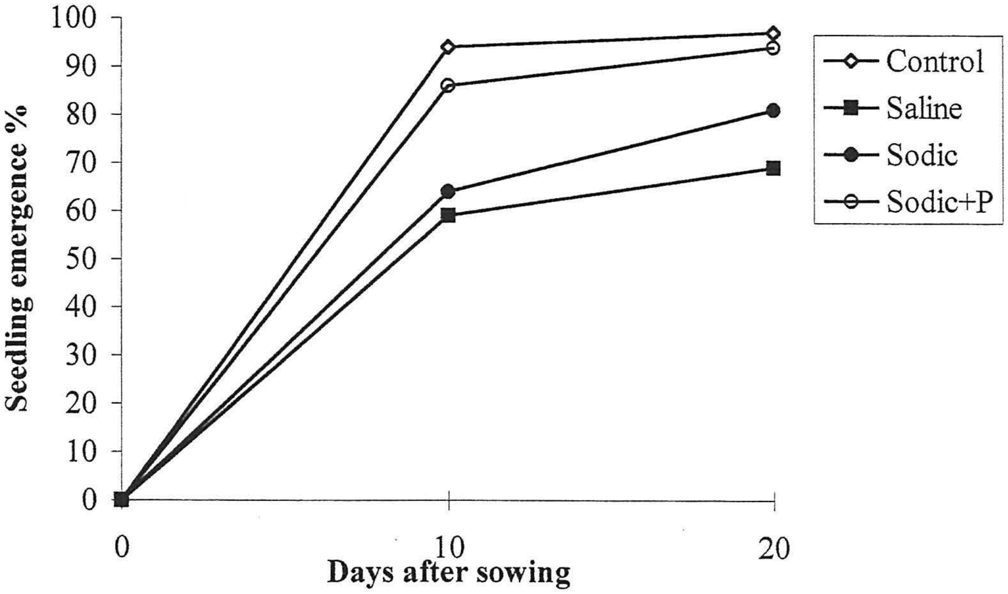


Figure 5.1. Effect of salt-affected soil treatments, on seedling emergence of wheat recorded at 10 and 20 DAS, under clay loam soil condition. Values are the means of 8 hexaploid wheat varieties.

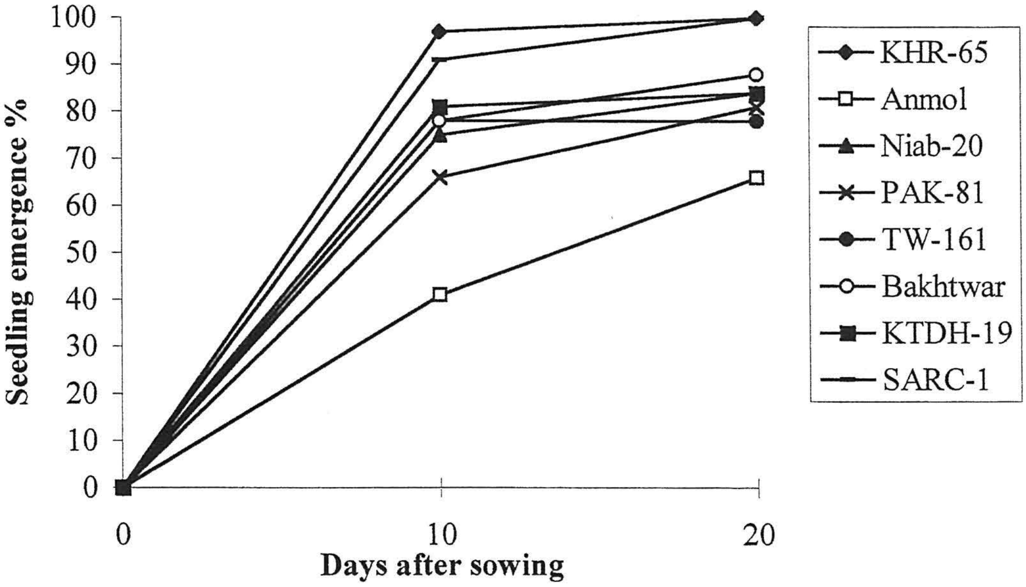


Figure 5.2. Effect of hexaploid wheat varieites on seedling emergence recorded at 10 and 20 DAS, under clay loam soil condition. Values are the means of 4 soil treatments (control, saline, sodic and sodic + PAM).

However, there was a greater delay in emergence in the sodic soil treatment, than in the saline soil treatment. Treating the sodic soil with PAM resulted in a small but significant increase in seedling emergence %. Differences between varieties were also evident (Figure 5.2). Anmol had significantly lower seedling emergence than other varieties at both stages. Although, the interaction of soil treatments x varieties was not statistically significant, the results (Table 5.1.1) suggested that the effects of salt treatments on different varieties were different. Kharchia-65 and SARC-1 showed higher final mean seedling emergence % than other varieties in all treatments. Treatment of sodic soil with PAM resulted (Table 5.1.1) in a significant increase in emergence % of some varieties (TW-161, Anmol and NIAB-20) but not others (e.g. PAK-81 and KTDH-19).

Table 5.1.1. Effect of high salinity and high sodicity with and without PAM on seedling emergence (%) of 8 wheat varieties, under clay loam soil condition, recorded at 20 DAS

	Soil treatments				
Variety	Control	Saline	Sodic	Sodic +PAM	Means
Khar-65	100	100	100	100	100.0
Anmol	75	38	50	100	65.6
NIAB-20	100	50	88	100	84.4
PAK-81	100	75	75	75	81.3
TW-161	100	63	50	100	78.1
Bakhtwar	100	63	100	88	87.5
KTDH-19	100	63	88	88	84.4
SARC-1	100	100	100	100	100.0
Means	96.8	68.8	81.2	93.7	
	Transformed data [arcsine (%/100)]				
Khar-65	1.57	1.57	1.57	1.57	1.57
Anmol	1.17	0.58	0.78	1.57	1.03
NIAB-20	1.57	0.78	1.37	1.57	1.32
PAK-81	1.57	1.17	1.17	1.17	1.28
TW-161	1.57	0.98	0.78	1.57	1.23
Bakhtwar	1.57	0.98	1.57	1.37	1.37
KTDH-19	1.57	0.98	1.37	1.37	1.32
SARC-1	1.57	1.57	1.57	1.57	1.57
Means	1.52	1.08	1.27	1.47	

Standard error of the difference between means (S. E. D.) and least significant difference (L. S. D.) for transformed data

Soil treatments		Variety		Soil trt:*Variety	
S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
0.088	0.176* * *	0.126	0.25* * *	0.251	N. S

5.3.3.3 Effects on seedling growth

The effects of salt-affected soil treatments on shoot height, shoot dry weight and root length are shown in Table 5.1.2. Seedlings in salt- affected soil treatments were significantly shorter than in the control. The effect of sodicity on shoot height was significantly greater than that of salinity. Treatment of sodic soil with PAM resulted in a small but significant increase in plant height. There were also small but significant differences in mean shoot height between varieties. The interaction of soil treatments x varieties was also significant. Differences in height between varieties were greater under saline and sodic conditions, than in the control and sodic soil + PAM treatment. In some varieties (Bakhtwar, KTDH-19, SARC-1 and NIAB-20) the effects of sodicity on plant height were greater than the effects of salinity, but in others (Anmol, PAK-81 and Kharchia-65) the effects of both salinity and sodicity were more or less similar.

Treatment of sodic soil with PAM resulted in a small but significant recovery of shoot height in some varieties (TW-161, Anmol and PAK-81) but not in others.

Shoot dry weight of seedlings in salt-affected soil treatments was also significantly lower than in the control. Similarly as it was in shoot height, the effect of sodicity was significantly greater than that of salinity. The interaction of soil treatments x varieties was also significant. NIAB-20 and SARC-1 had high shoot dry weight/plant in both saline and sodic conditions. Varieties with low shoot dry weight under saline conditions (Anmol and PAK-81) also had low shoot dry weight under sodic conditions. In some varieties (Bakhtwar and KTDH-19) the effects of salinity and sodicity on shoot dry weight were similar, but in others (Kharchia-65, NIAB-20 and SARC-1) they were significantly different. The treatment of sodic soil with PAM also resulted in a significant increase in shoot dry weight of some varieties (Kharchia-65, PAK-81 and TW-161) but not others. Root length of seedlings was also significantly shorter in salt-affected soil treatments than in the control. The effect of sodicity was significant and more severe than the effect of salinity. The difference between varieties for root length was non significant. But the interaction of soil treatments x varieties was significant. In the saline soil treatment PAK-81 and TW-161 had a shorter root system than other varieties. In the sodic soil treatments seedlings of all varieties had very short root systems and PAM had no positive or negative effect on root length.

Table 5.1.2. Effect of high salinity and high sodicity with and without PAM on shoot height, shoot dry weight and root length of 8 wheat varieties, harvested at 10 DAS under clay loam soil condition

	Soil treatments				
Variety	Control	Saline	Sodic	Sodic +PAM	Means
		Shoot height (cm)			
Kharchia-65	16	9	7	6	9.2
Anmol	16	3	3	5	6.5
NIAB-20	13	8	5	6	8.1
PAK-81	17	5	3	5	7.4
TW-161	17	4	1	6	6.9
Bakhtwar	14	9	5	6	8.7
KTDH-19	14	9	5	5	8.6
SARC-1	13	11	5	6	8.8
Means	15.2	7.2	4.1	5.5	
		Shoot dry wt /plant (mg)			
Kharchia-65	26	15	7	13	15.4
Anmol	21	4	8	10	10.9
NIAB-20	21	17	10	11	15.1
PAK-81	24	2	4	11	10.1
TW-161	26	9	3	11	12.3
Bakhtwar	25	11	12	9	13.9
KTDH-19	32	11	13	12	17.1
SARC-1	24	20	12	9	16.4
Means	24.7	11.2	8.8	10.7	
		Root length (cm)			
Kharchia-65	7	6	1	1	7.2
Anmol	7	4	1	1	7.0
NIAB-20	8	6	1	1	7.8
PAK-81	7	2	1	1	7.4
TW-161	11	3	0	1	11.0
Bakhtwar	10	5	1	1	10.4
KTDH-19	10	4	1	1	9.6
SARC-1	8	5	1	1	8.0
Means	8.5	4.4	0.8	1.0	

	Soil treatment		Variety		Soil treatment*Variety	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
Height	0.4	0.7* * *	0.5	1.1* * *	1.1	2.1* * *
Dry weight	1.0	1.9* * *	1.4	2.8* * *	2.8	5.6* * *
Root length	0.3	0.6* * *	0.4	N. S	0.9	1.7* * *

5.4 Experiments 3 and 4

The results of Experiment 2 showed that under clay loam soil conditions the effects of sodicity were to delay emergence and to decrease seedling growth of wheat. The performance of different varieties in the presence or absence of PAM was also different. It is possible that the effects of sodicity and PAM vary with soil texture. It was therefore decided to perform two further experiments, to study wheat growth at the seedling stage in different soils (loamy sand and clay loam) with poor and stable soil structure, using PAM. For these experiments some varieties were selected from Experiment 1. Other varieties (salt tolerant and sensitive) along with 4 durum wheat genotypes (having a K^+/Na^+ ratio discrimination character) were also incorporated to test their performance in the presence of PAM. Leaf samples were taken and analysed for ion content to determine the effects of sodicity and PAM on Na^+, K^+, Ca^{2+} and Mg^{2+}, with the aim of studying the relationship between the performance of a variety and ion uptake.

These 2 experiments were started with the following objectives in mind:

(1). To determine whether the effects of sodicity on seedling emergence, ion uptake and growth depend on soil texture;

(2). To determine whether the ability of PAM to recover the adverse effects of sodicity depends on soil texture;

(3). To determine whether soil texture influences the tolerance/ sensitivity of different wheat varieties/genotypes;

(4). To determine the effects of soil texture and PAM on ion uptake under sodic conditions.

5.4.1 Materials and Methods

These two experiments were performed to study the effect of different ESP levels and PAM on emergence, growth and ion uptake of wheat seedlings. Two experiments were performed, one using clay loam soil and one using loamy sand soil. Each experiment had the following treatments: Control, Low ESP, Low ESP with PAM, Medium ESP, Medium ESP with PAM, High ESP and High ESP with PAM.

5.4.1.1 Soil preparation

Soil in bulk (plough layer) was collected from the Caeglanmor field of College Farm, University of Wales, Bangor, UK. The field had been cropped with grass and used for silage and grazing for the last three years.

5.4.1.1.1 Loamy sand soil

The clay loam soil of Caeglanmor field was diluted by mixing with sand to obtain a loamy sand soil with approximately 9 % clay content.

5.4.1.1.2 Sodic soil.

To establish low, medium and high ESP levels, three lots of each of the loamy sand and clay loam soil were sprayed with 0.25M, 0.5M and 0.75M $NaHCO_3$ solution respectively, following the methods described in the Chapter 3 (Section 3.1.1).

5.4.1.1.3 PAM application

To stabilise the soil structure in the presence of exchangeable sodium, half of that artificially alkalised soil was again treated with PAM at the rate of 0.2 kg/100 kg of soil. The method for preparation of sodic soil and application of PAM is described in Chapter 3 (Section 3.1).

5.4.1.1.4 Growth conditions

These experiments were conducted in a glasshouse during the period December 1997- January, 1998. The temperature of the glasshouse was not controlled. Natural day light was supplemented with 250 watt sodium lamps, to extend the day length to 16 hours.

5.4.1.1.5 Seed sowing

The seeds of hexaploid wheat cultivars (Avalon, Q-19, NIAB-20, KRL1-3, Kharchia-65 and Bakhtwar) and tetraploid wheat genotypes ($R173^+$, $R21^-$, $R23^-$, and $R\ 112^+$), were sown in pots (53 cm x23 cm surface x16cm deep) on 4th of December 1997. The methods for seed sowing, applying irrigation water and fertiliser to each pot were as in Experiment 1. There was a single pot of each treatment and 8 replicate plants of each variety per pot.

5.4.1.1.6 Recording of seedling emergence, sampling of young fully expanded leaf and final harvest

All emerged seedlings were counted 5, 10, 15, 20 and 25 days after sowing in each experiment. At 58 DAS all plants from each treatment were harvested, by cutting at the soil surface. Shoot height, number of fully expanded leaves on the main stem and number of tillers per plant were determined. The youngest fully expanded leaf was removed from four plants for sap extraction and ion analysis. In Kharchia-65, Bakhtwar, NIAB-20, KRL1-3, Q-19 and genotype R173$^+$, leaves were sampled from the plants grown in the control, medium ESP and medium ESP plus PAM treatments. In Avalon, R23$^-$, R21$^-$, and R112$^+$ the leaves were very small and so as to have sufficient sap leaves were sampled from the control, low ESP and low ESP with PAM treatments. The remaining germinated plants from the above treatments and from all other treatments were oven dried at 82 °C for 48 hours, and their dry weight was recorded.

5.4.1.1.7 Soil analyses

Before sowing and after harvesting of seedlings, a composite sample of soil from each pot was collected and analysed for chemical (Na^+, K^+, Ca^{2+}, Mg^{2+}, pH, EC_e, total N % and total C %) and physical properties (soil texture and Water Stable Aggregates % (WSA %)).

5.4.1.1.8 Statistical analyses

The data from the 7 treatments were combined and analysed by performing analysis of variance with the Minitab statistical package using the method described in Section 5.3.2.6.

The data for seedling emergence, number of fully expanded leaves, number of tillers (per plant) and shoot height were analysed using 8 replicates. The data for ion concentrations and dry weight were analysed using four replicates. In this experiment each single plant was considered as a replicate. Values of the L. S. D. and S. E. D. were calculated using the formulae given in Chapter 4 (Section 4.3.7).

Due to the larger differences in the values of Na^+ and K^+/Na^+ ratio between the control and sodic treatments, separate analyses were performed on these data by excluding the control values.

5.5 Results of Experiment 3

Effects of soil sodicity and PAM on the emergence, ion uptake and growth at an early seedling stage under loamy sand soil conditions

5.5.1 Effects of sodium bicarbonate salt solution and PAM on soil properties

The effects of sodium bicarbonate salt solution and PAM on pH, EC_e (dSm^{-1}), SAR, ESP and WSA% are shown in Table 5.2. Soil pH increased as the concentration of sodium bicarbonate added increased. Treatment of soil with PAM decreased pH, especially at the high sodicity level. There were slight decreases in soil pH during the course of the experiment.

The electrical conductivity of the control soil was low (non-saline). However, EC_e increased with increasing salt concentration. The results provided no evidence that the treatment of sodic soil with PAM resulted in a change in EC_e. In the treated soil EC_e was higher after harvesting of the seedlings than before sowing but in the control it was markedly lower.

SAR and ESP of the soil increased with increasing salt concentration but decreased slightly between sowing and harvest. PAM had no clear effect on SAR and ESP either before sowing or after harvesting of the seedlings.

Sodicity had a very large effect on the % of water stable aggregates (WSA). As sodicity increased so the % WSA decreased in the treatments without PAM. Treatment of soil with PAM increased the % WSA, at low and medium sodicity to values 15 and 10 % higher than the control and at high sodicity to a value similar to the control.

Table 5.2. pH, electrical conductivity (EC_e), sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), % water stable aggregates (%WSA), total carbon and nitrogen (%) and texture of the soil before sowing and after harvest

Before sowing

Treatment	$NaHCO_3$ added	pH (H_2O)	EC_e (dSm^{-1})	SAR	ESP
Control	No salt	7.5	4.4	6	7
Low	0.25M	8.2	4.6	16	18
Low + PAM	0.25M	8.0	4.8	16	18
Medium	0.50M	9.5	5.5	28	29
Medium + PAM	0.50M	9.2	5.5	28	32
High	0.75M	10.0	6.5	43	39
High + PAM	0.75M	9.6	6.4	44	39

Total carbon % (control soil) = 1.75 (before sowing)
Total nitrogen % (control soil) = 0.09 (before sowing)

Texture (Sedigraph method)

Sand total	= 78.5 %
2000 ------630µm	= 2.8 %
630µm ------200µm	= 65.9 %
200µm--------63µm	= 9.9 %
Silt------------------------	= 12.9 %
Clay-----------------------	= 8.6 %

Textural class

UK classification	= Loamy sand
USDA classification	= Loamy sand

After harvest

Treatment	$NaHCO_3$ added	pH (H_2O)	EC_e (dSm^{-1})	SAR	ESP	Water stable aggregates (%)
Control	No salt	7.6	0.8	5	6	82
Low	0.25M	8.2	6.4	14	16	61
Low + PAM	0.25M	8.0	6.0	14	17	95
Medium	0.50M	9.4	6.0	26	27	38
Medium + PAM	0.50M	9.0	6.0	26	27	91
High	0.75M	9.8	10.0	41	38	33
High + PAM	0.75M	9.0	10.0	40	37	80

5.5.2 Effects on seedling emergence (%)

The effects of sodicity and PAM on seedling emergence over time are presented in Figure 5.2.1. The results showed that seedling emergence was decreased and delayed with increasing sodicity. The final emergence (Table 5.21) was 15 % lower at medium sodicity and 20 % lower at high sodicity than in the control. The effect of PAM was evident from 10 DAS. Treatment of soil with PAM increased seedling emergence at 25 DAS by 21 % at medium sodicity and 24 % at high sodicity. At low sodicity PAM delayed emergence. Seedling emergence in the low ESP plus PAM treatment was lower than in the low ESP treatment at 5 and 10 DAS.

Figure 5.2.2 shows that at 5 DAS in most of the varieties (average of all treatments) seedling emergence was below 20 %. Significant differences between varieties in seedling emergence were apparent at 10 DAS, and these generally remained persistent at 15, 20 and 25 DAS. There were large differences between the varieties in the effects of sodicity and PAM on the pattern of seedling emergence. Amongst the hexaploid wheat varieties at all sampling dates Q-19 showed the fastest emergence and was least affected by sodicity (Figure 5.2.3d), Avalon (Figure 5.2.3e) and KRL1-3 (Figure 5.2f) showed the slowest emergence and the greatest effect of sodicity. The other hexaploid wheat varieties were intermediate. In the durum wheat genotypes, seedling emergence of genotypes R112^{+}, R21^{-} and R23^{-} was delayed and decreased markedly by high sodicity, but the emergence of R173^{+} was little affected (Figures 5.2.3g, h, i and j). The effect of soil treatment with PAM was effective in increasing the emergence of almost all varieties in all sodicity treatments, except Avalon which showed a negative response to PAM at high sodicity (Figures 5.2.3, 5.2.3.1 and Table 5.2.1).

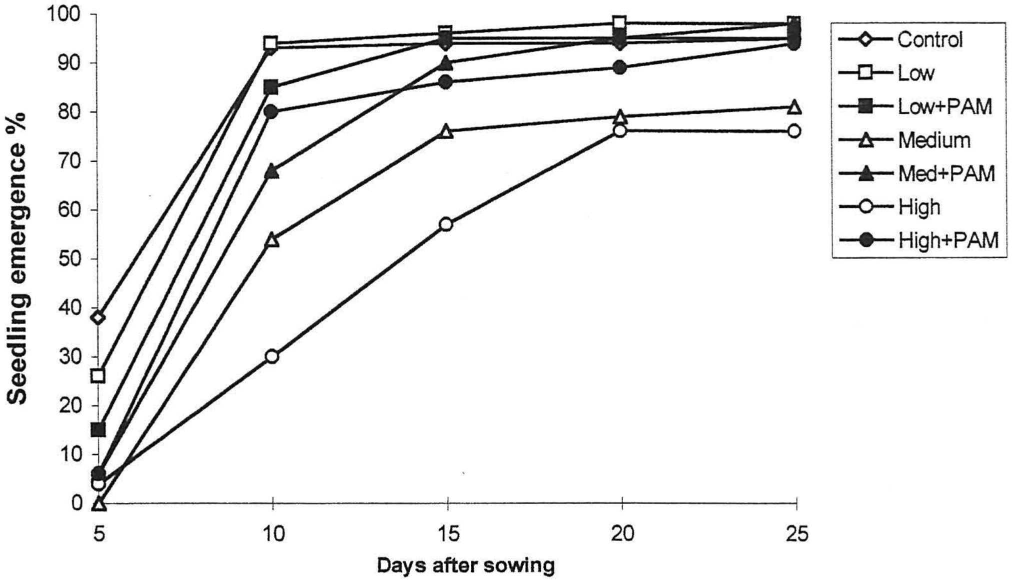


Figure 5.2.1. Main effect of sodicity and PAM on seedling emergence (%) of wheat under loamy sand soil condition (data are the average of 10 varieties)

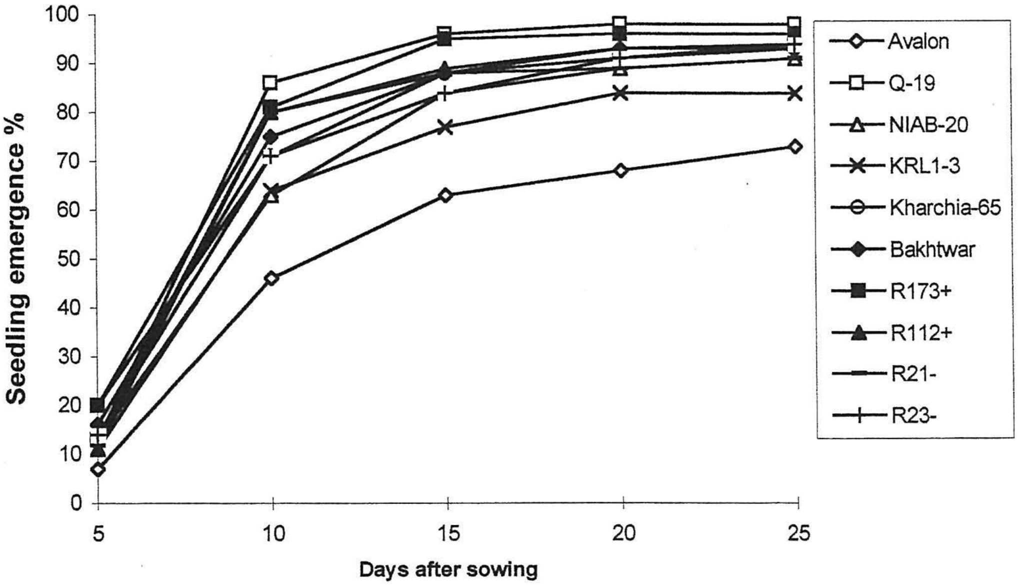


Figure 5.2.2. Effect of varieties on seedling emergence (%) of wheat under loamy sand soil condition (data are the average of 7 soil treatments)

Table 5.2.1. Effect of sodicity and PAM on seedling emergence (%) of 4 durum wheat genotypes and 6 hexaploid wheat varieties recorded at 25 DAS, under loamy sand soil condition

		Exchangeable sodium percentage						
	Control	Low		Medium		High		
Variety	7	18	18^{PAM}	29	32^{PAM}	39	39^{PAM}	Means
		Seedling emergence % , 25 DAS						
Durum wheat genotypes								
R173^{+}	100	100	100	88	88	100	100	96.4
R112^{+}	100	100	100	88	100	75	100	94.6
R 21^{-}	100	100	88	88	100	63	100	91.0
R 23^{-}	100	100	100	75	100	88	100	94.6
Hexaploid wheat varieties								
Khar- 65	100	100	100	88	100	63	100	92.8
Bakhtwar	88	100	100	75	100	88	100	92.8
NIAB-20	100	88	100	75	88	88	100	91.0
KRL1-3	88	88	88	63	100	63	100	83.9
Q-19	100	100	100	100	100	88	100	98.2
Avalon	75	100	75	75	100	50	38	73.2
Means	95.0	97.5	95.0	81.2	97.5	76.2	93.7	
		Transformed data [arcsine (%/100) values]						
Durum wheat genotypes								
R173^{+}	1.57	1.57	1.57	1.37	1.37	1.57	1.57	1.51
R112^{+}	1.57	1.57	1.57	1.37	1.57	1.17	1.57	1.48
R 21^{-}	1.57	1.57	1.37	1.37	1.57	0.98	1.57	1.43
R 23^{-}	1.57	1.57	1.57	1.17	1.57	1.37	1.57	1.48
Hexaploid wheat varieties								
Khar- 65	1.57	1.57	1.57	1.37	1.57	0.98	1.57	1.45
Bakhtwar	1.37	1.57	1.57	1.17	1.57	1.37	1.57	1.45
NIAB-20	1.57	1.37	1.57	1.17	1.37	1.37	1.57	1.43
KRL1-3	1.37	1.37	1.37	0.98	1.57	0.98	1.57	1.31
Q-19	1.57	1.57	1.57	1.57	1.57	1.37	1.57	1.54
Avalon	1.17	1.57	1.17	1.17	1.57	0.78	0.58	1.15
Means	1.49	1.53	1.49	1.27	1.53	1.19	1.47	

Standered error of the difference between means (S. E. D.) and least significant difference (L. S. D.) for transformed data

	Sodicity	Variety	Var*Sodicity
S. E. D.	0.067	0.080	0.212
L. S. D.	0.133* * *	0.158* * *	N. S

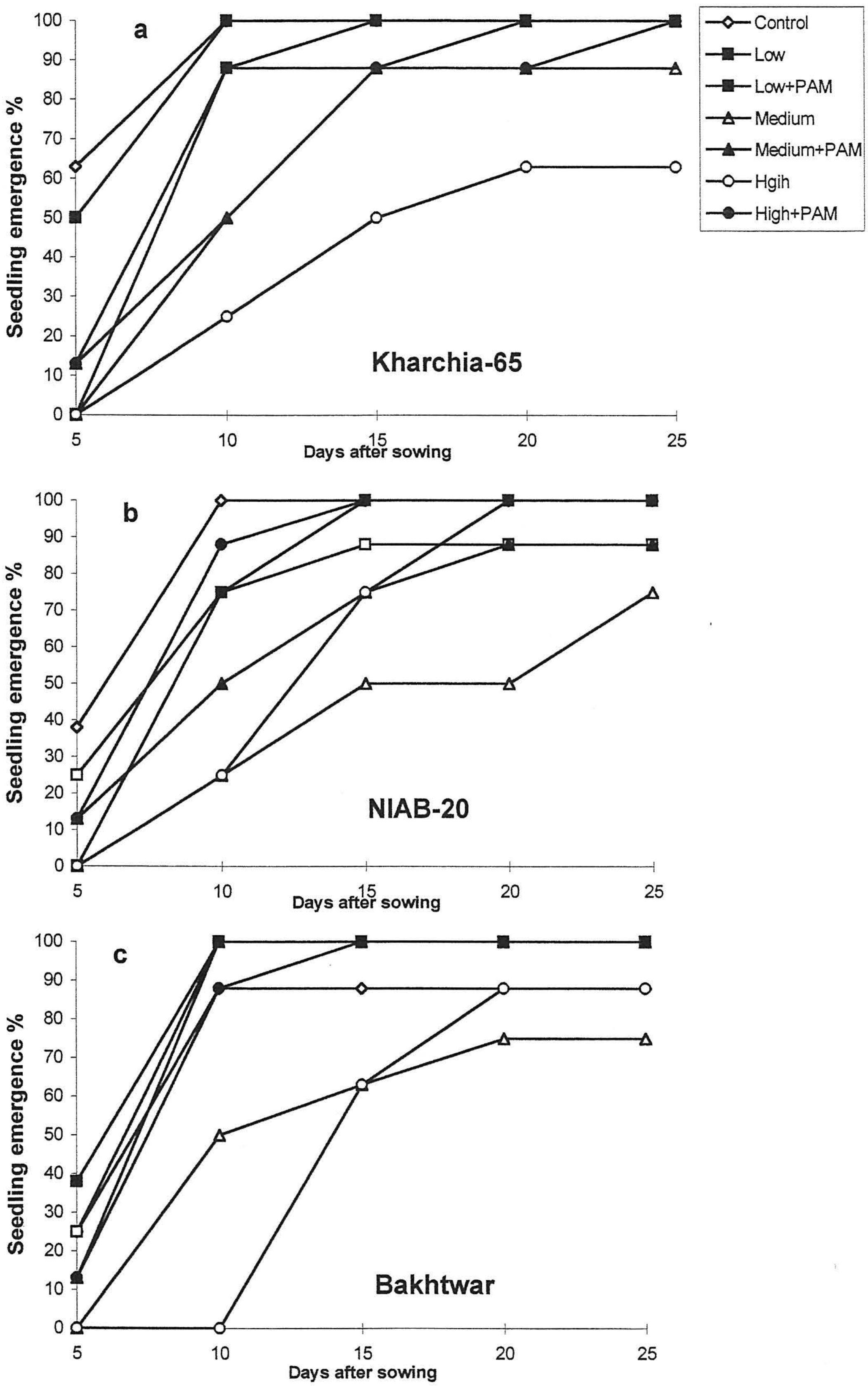


Figure 5.2.3. Effect of sodicity and PAM on seedling emergence of (a) Kharchia-65, (b) NIAB-20 and (c) Bakhtwar under loamy sand soil condition

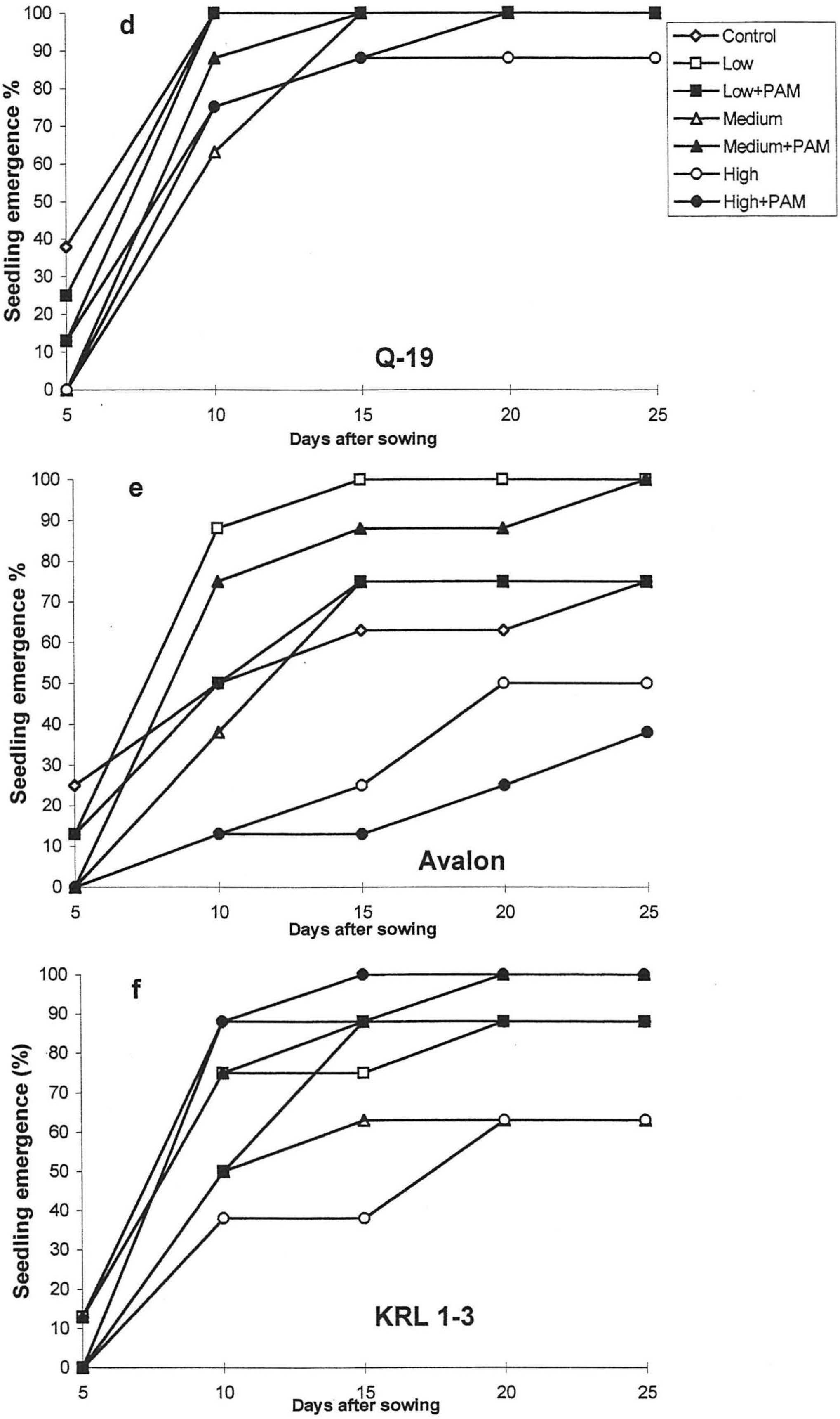


Figure 5.2.3. Effect of sodicity and PAM on seedling emergence of (d) Q-19 (e), Avalon and (f) KRL1-3 under loamy sand soil condition

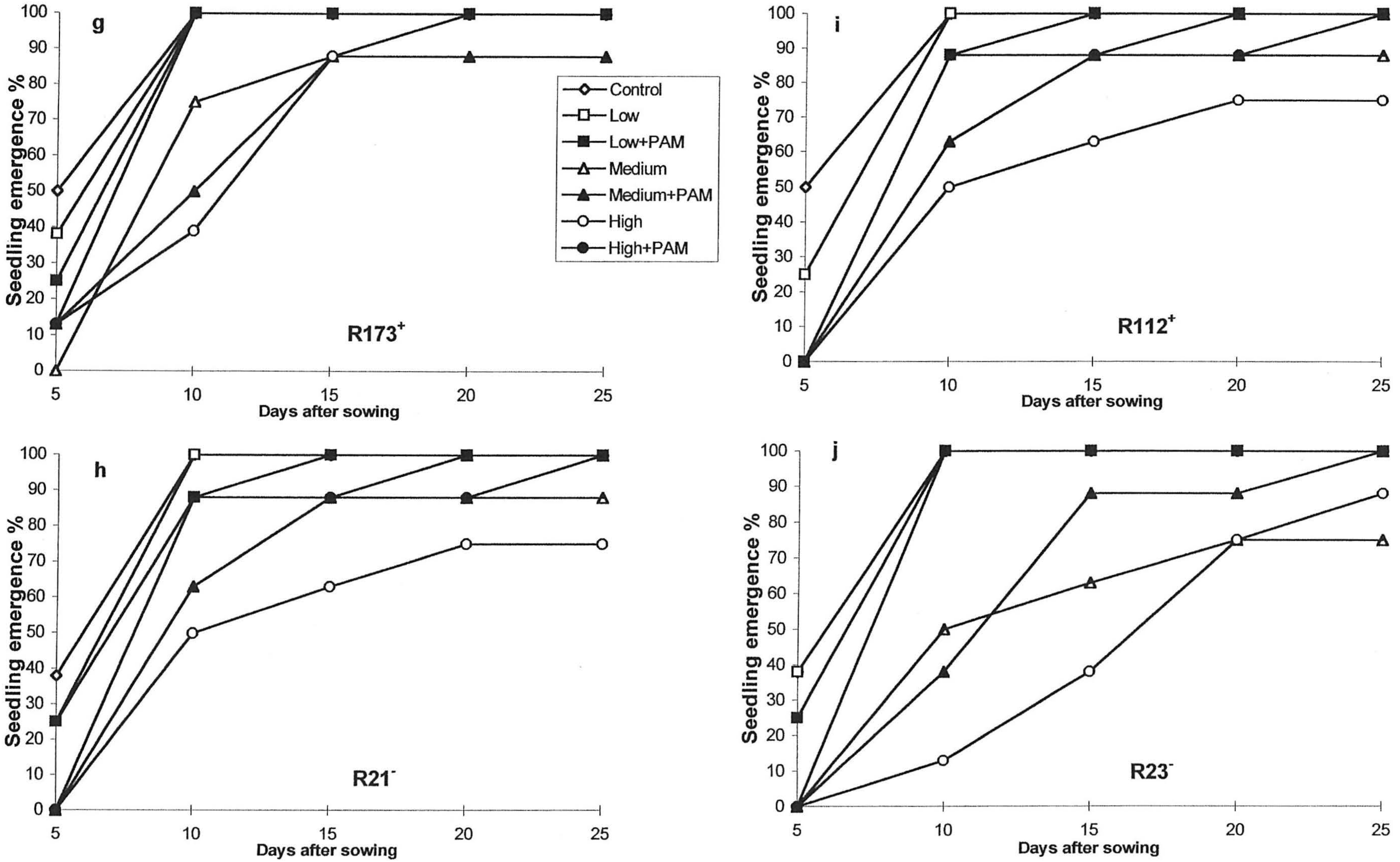


Figure 5.2.3. Effect of sodicity and PAM on seedling emergence (%) of (g) R173+ (h) R21- (i) R112+ and (j) R23- durum wheat genotypes under loamy sand soil condition.

5.5.3 Effects on ion concentration in:

5.5.3 (a) Five hexaploid wheat varieties and 1 durum wheat genotype at medium ESP and in medium ESP plus PAM treated soil

Sodicity had a marked effect on ion concentration in the youngest fully expanded leaf sap of these cultivars (Table 5.2.3a). Compared to the untreated control the concentration of $Na^+$was increased while that of K^+, Ca^{2+} and Mg^{2+} were decreased by sodicity. The decrease in K^+ and increase in Na^+ led to lower K^+/Na^+ ratio in the sodic treatment. Treatment of sodic soil with PAM resulted in a significantly lower concentration of Na^+, significantly higher concentration of K^+, a small but non significant increase in the concentration of Ca^{2+}, and increased K^+/Na^+ ratio compared to the sodic treatment. PAM had no effect on Mg^{2+}. There were differences in ion concentration between the varieties. R173$^+$ had lower K^+, and significantly higher Na^+ concentration than the other varieties. Q-19 had significantly lower Na^+ than other varieties. Treatment of sodic soil with PAM resulted in a decrease in Na^+ in flag leaf sap of all varieties, but this decrease was statistically significant only in R173$^+$, KRL1-3 and Kharchia-65.

5.5.3 (b) One hexaploid wheat variety and three durum wheat genotypes at low ESP and in low ESP plus PAM treated sodic soil

Analysis of variance indicated that sodicity treatment had a significant effect on ion concentration in the youngest fully expanded leaf sap of these genotypes (Table 5.2.3 b). The effect of sodicity was to significantly increase Na^+, and significantly decrease K^+, Ca^{2+}, Mg^{2+} and K^+/Na^+ ratio. Treatment of sodic soil with PAM significantly decreased the concentration of Na^+ and increased the concentration of K^+ and K^+/Na^+ ratio (when control values were excluded). It also resulted in small but non significant increases in $Ca^{2+}$and Mg^{2+}. There were differences in ion concentration between the genotypes. Avalon and R112$^+$ had lower Na^+ but higher K^+, Ca^{2+} and Mg^{2+} than R21$^-$ and R23$^-$. Treatment of sodic soil with PAM resulted in a decrease in Na^+ in leaf sap of all varieties. This decrease was greater in Avalon, R21$^-$ and R112$^+$ than in R23$^-$. Of the genotypes tested at low ESP level, Avalon showed the highest response to PAM, showing the largest decrease in Na^+ and greatest increase in K^+.

Table 5.2.3 (a). Effect of sodicity and PAM on the concentrations of Na^+, K^+, Ca^{2+} and Mg^{2+} and K^+/Na^+ ratio in the sap extracted from youngest fully expanded leaf of 6 hexaploid wheat varieties and 1 durum wheat genotype under loamy sand soil condition

Ion (mol m^{-3})	ESP	Varieties						
		R173$^+$	Q-19	NIAB-20	KRL1-3	Khar-65	Bakh:	Means
Na^+	7	13	9	15	3	2	7	8.0
	29	455	84	261	282	204	272	259.6
	32+PAM	250	53	203	94	118	217	155.7
	Means	239.2	48.4	159.4	126.1	107.9	165.6	
K^+	7	289	378	318	362	480	357	364.8
	29	120	283	305	245	342	213	251.1
	32+PAM	265	386	320	318	380	302	328.5
	Means	224.6	349.1	314.3	308.3	400.6	290.7	
K^+/Na^+	7	23.0	48.0	22.0	136.0	240.0	52.0	87.7
	29	0.3	4.0	1.2	1.0	2.0	1.0	1.4
	32+PAM	1.1	17.0	2.0	3.4	4.0	1.4	4.7
	Means	8.3	22.6	8.5	46.6	81.7	17.9	
Ca^{2+}	7	21	40	32	38	30	25	30.7
	29	9	15	9	14	10	9	10.8
	32+PAM	12	15	12	12	16	12	13.0
	Means	13.6	23.2	17.4	21.0	18.5	15.3	
Mg^{2+}	7	30	46	45	17	13	31	30.2
	29	16	17	15	16	16	13	15.1
	32+PAM	13	22	13	14	15	16	15.6
	Means	19.5	28.1	24.4	15.6	14.5	19.7	

	Sodicity		Variety		Sodicity * Variety	
	S. E. D	L. S. D	S. E. D	L. S. D	S. E. D	L. S.D
Na^+	14.4	29.2* * *	20.3	41.3* * *	35.2	71.5* * *
K^+	21.2	43.0* * *	25.2	51.2* * *	52.0	N. S
K^+/Na^+	4.60	9.30* * *	6.50	13.0* * *	11.20	23.0* * *
Ca^{2+}	2.0	4.0* * *	3.0	5.4* *	5.0	N. S
Mg^{2+}	2.0	4.0* * *	3.0	5.2* * *	4.4	9.0* * *
Analyses excluding control treatment values						
Na^+	17.6	35.7* * *	30.4	61.9* * *	43.1	87.6*
K^+/Na^+	1.25	2.55*	2.17	4.42* *	3.76	N. S

Table 5.2.3 (b). Effect of sodicity and PAM on the concentrations of Na^+, K^+, Ca^{2+} and Mg^{2+} and K^+/Na^+ ratio in the sap extracted from youngest fully expanded leaf of 4 durum wheat genotypes and 1 hexaploid wheat variety grown under loamy sand soil condition

Ion (mol m^{-3})	ESP	Genotypes				
		Avalon	$R112^+$	$R21^-$	$R23^-$	Means
Na^+	7	5	32	153	135	81.2
	18	133	258	400	527	329.5
	18+PAM	45	210	324	503	270.1
Means		61.0	166.4	292.0	388.3	
K^+	7	366	240	185	130	230.2
	18	210	210	135	25	144.9
	18+PAM	320	214	153	80	191.8
Means		298.7	221.4	157.5	78.2	
K^+/Na^+	7	75.0	13.0	1.5	1.0	22.45
	18	2.0	1.0	0.3	0.1	0.82
	18+PAM	7.0	1.0	0.5	0.2	2.23
Means		27.97	4.83	0.76	0.44	
Ca^{2+}	7	21	32	16	19	21.6
	18	17	17	6	6	11.0
	18+PAM	24	19	10	10	15.5
Means		20.1	22.4	11.3	10.3	
Mg^{2+}	7	30	33	23	28	28.3
	18	24	25	9	9	16.6
	18+PAM	24	20	15	15	18.4
Means		25.6	26.0	17.1	15.5	

	Sodicity		Genotypes		Sodicity*Genotypes	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
Na^+	22.1	45.0* * *	26.0	52.0* * *	44.3	90.0* *
K^+	15.0	30.4* * *	17.1	35.0* * *	29.7	N. S
K^+/Na^+	2.10	4.23* * *	2.41	4.90* * *	4.17	8.50* * *
Ca^{2+}	2.5	5.1* *	2.9	5.9* * *	5.0	N. S
Mg^{2+}	2.6	5.4* * *	3.1	6.2* *	5.3	N. S
Analyses excluding control treatment values						
Na^+	25.4	52.4*	35.9	74.1* * *	50.8	N. S
K^+/Na^+	0.30	0.62* * *	0.42	0.87* * *	0.36	0.74* * *

5.5.4 Effects on growth and development

The effects of sodicity and PAM on the growth and development of wheat seedlings are presented in Tables 5.2.4 and 5.2.5. The results show that the seedlings grown at medium and high sodicity were significantly shorter than those grown at control and low sodicity. Treatment of soil with PAM resulted in a significant increase in

Table 5.2.4. Effect of sodicity with and without PAM on height and shoot dry weight of tetraploid wheat genotypes and durum wheat varieties, grown under loamy sand soil condition, harvested at 58 DAS

	Exchangeable sodium percentage							
	Control	Low		Medium		High		
Variety	7	18	18^{PAM}	29	32^{PAM}	39	39^{PAM}	Means
				Height (cm)				
Durum wheat genotypes								
R173$^+$	48	46	40	29	32	11	39	34.9
R112$^+$	39	43	43	30	34	12	36	33.7
R 21$^-$	41	40	33	24	30	7	27	28.8
R 23$^-$	43	36	39	17	31	9	26	28.6
Hexaploid wheat varieties								
Kharchia- 65	56	58	53	51	57	15	60	50.1
Bakhtwar	38	44	44	30	41	12	42	35.7
NIAB-20	40	37	43	26	33	18	41	33.4
KRL1-3	34	35	34	21	45	12	41	31.6
Q-19	39	39	41	27	41	12	37	33.7
Avalon	37	34	35	21	36	7	9	25.5
Means	41.4	41.1	40.1	27.6	38.0	11.5	35.8	
				Shoot dry wt /plant (mg)				
Durum wheat genotypes								
R173$^+$	470	345	227	110	206	26	292	240.0
R112$^+$	207	277	151	143	182	18	247	174.8
R 21$^-$	301	216	137	63	102	12	138	138.5
R 23$^-$	258	154	146	54	103	16	78	115.7
Hexaploid wheat varieties								
Kharchia- 65	469	500	427	313	560	66	500	381.5
Bakhtwar	107	245	278	137	308	41	358	210.5
NIAB-20	289	168	264	101	238	33	249	191.8
KRL1-3	117	226	306	118	352	38	217	196.2
Q-19	298	302	291	124	279	25	289	229.5
Avalon	121	233	129	151	250	30	114	146.5
Means	263.7	266.5	236.8	131.2	245.7	30.6	243.0	

		Sodicity	Variety	Var*Sodicity
Height	S. E. D.	2.0	2.0	5.3
	L. S. D.	3.3* * *	4.0* * *	11.0* * *
Shoot dry wt	S. E. D.	26.0	31.0	81.0
	L. S. D.	52.0* * *	62.0* * *	164.0*

height at medium and high ESP. At high ESP the increase in height was significant in all varieties except Avalon. In the high sodicity plus PAM treatment, apart from a few varieties (R21$^-$, R23$^-$ and Avalon), shoot height of all other varieties was not significantly different from the control.

Similarly sodicity also resulted in a significant decrease in shoot dry weight, (Table 5.2.4) but when soil was treated with PAM shoot dry weight was markedly increased. Overall varieties, PAM increased shoot dry weight at medium and high ESP, but not at low ESP. Bakhtwar and NIAB-20 had very low shoot dry weight in the control treatment. In the medium and high ESP treatments with PAM, except for genotypes R173$^+$, R21$^-$ and R23$^-$, Shoot dry weight in all varieties was not significantly lower than that of the control.

At high sodicity seedlings had fewer fully expanded leaves on their main stem (Table 5.2.5). However, there was no significant difference between the seedlings grown at medium sodicity and the control. Contrarily the seedlings grown at low sodicity with and without PAM had slightly more leaves compared to the control. The number of fully expanded leaves on the main stem was increased by PAM at high sodicity in all varieties except Avalon. Seedlings in the high sodicity plus PAM treatment had equal number of fully expanded leaves on main stem as the control.

At low and medium sodicity seedlings had 50% fewer tillers and at high sodicity seedlings had no tillers at all (Table 5.2.5). Treatment of sodic soil with PAM resulted in a significant increase in tillers at high ESP. The effect of PAM at high ESP was significant in all varieties except R23$^-$ and KRL1-3, which produced no tillers.

Table 5.2.5. Effect of sodicity with and without PAM on number of fully expanded leaves on the main stem/plant and number of tillers /plant in durum wheat genotypes and hexaploid wheat varieties grown under loamy sand soil condition, harvested at 58 DAS

	Exchangeable sodium percentage							
	Control	Low		Medium		High		
Variety	7	18	18^{PAM}	29	32^{PAM}	39	39^{PAM}	Means
			No. of fully expanded leaves on the main stem/plant					
Durum wheat genotypes								
R173$^+$	4	6	5	4	4	2	4	4.0
R112$^+$	3	4	5	4	4	2	4	3.6
R 21$^-$	4	5	4	3	4	1	4	3.6
R 23$^-$	4	5	5	3	4	2	3	3.6
Hexaploid wheat varieties								
Kharchia- 65	5	5	4	4	5	2	5	4.4
Bakhtwar	5	5	5	4	5	2	5	4.5
NIAB-20	5	4	4	3	4	3	5	3.8
KRL1-3	4	4	4	3	4	2	5	3.6
Q-19	5	5	5	5	6	2	4	4.5
Avalon	4	4	4	3	4	2	2	3.2
Means	4.3	4.7	4.6	3.8	4.3	1.8	3.9	
			No. of tillers /plant					
Durum wheat genotypes								
R173$^+$	3	2	1	2	2	0	3	1.8
R112$^+$	2	2	1	2	2	0	2	1.4
R 21$^-$	3	1	2	1	1	0	1	1.0
R 23$^-$	2	0	0	0	1	0	0	0.4
Hexaploid wheat varieties								
Kharchia- 65	1	0	0	0	0	0	1	0.3
Bakhtwar	0	0	0	0	1	0	1	0.2
NIAB-20	2	0	0	1	1	0	1	0.6
KRL1-3	0	0	0	0	0	0	0	0.0
Q-19	1	1	0	1	2	0	1	0.6
Avalon	2	1	1	0	1	0	1	1.0
Means	1.5	0.7	0.6	0.6	1.0	0.0	0.9	

		Sodicity	Variety	Var*Sodicity
No. leaves/plant	S. E. D.	0.20	0.77	0.64
	L. S. D.	0.40* * *	1.52* * *	1.30* *
No. tillers/plant	S. E. D.	0.13	0.15	0.41
	L. S. D.	0.25* * *	0.30* * *	0.81* * *

5.6 Results of Experiment 4

Effects of sodicity and PAM on the emergence, ion uptake and growth, at an early seedling stage, under clay loam soil conditions

5.6.1 Effects of sodium bicarbonate salt solution on physical and chemical properties of clay loam soil

The results for soil physical and chemical properties presented in this section are based on a composite sample from each treatment with no replication.

The effects of sodium bicarbonate salt solution on soil physical and chemical properties before sowing and after harvesting of the seedlings are shown in Table 5.3. The pH of soil increased with increasing concentration of salt. At medium and high salt concentration (0.5 and 0.75M) the soil had a strongly alkaline pH. There was no large change in soil pH between sowing and harvesting of the seedlings. PAM had a very slight effect on soil pH before sowing, but, after harvesting it had no clear effect on pH.

Electrical conductivity (dSm^{-1}) of the soil before sowing increased slightly with the concentration of added $NaHCO_3$. However, after harvesting of the seedlings it increased more markedly with increasing sodicity. PAM had no consistent effect on the electrical conductivity of the soil (saturated paste).

Sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) of the soil increased with increasing concentration of sodium bicarbonate added. There were differences between the values observed before sowing and after harvesting of seedlings but the trends were not consistent at the different sodicity levels. The effect of PAM on SAR and ESP was not consistent before sowing. However, after harvesting of the seedlings, SAR and ESP were decreased by PAM at the highest concentration of $NaHCO_3$.

Sodicity had a very large effect on the percentage of water stable aggregates (% WSA). % WSA decreased with increasing sodicity. The decrease was 26, 45 and 52 % at low, medium and high sodicity respectively. Treatment of sodic soil with PAM increased the % WSA, at low and medium sodicity to values 15 and 10 % lower than the control and at high sodicity to a value 2 % greater than the control.

Table 5.3. pH, electrical conductivity (EC_e), sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), % water stable aggregates (%WSA), total carbon and nitrogen (%) and texture of the soil before sowing and after harvest

Before sowing

Treatment	$NaHCO_3$ added	pH (H_2O)	EC_e (dSm^{-1})	SAR	ESP
Control	No salt	6.0	2.0	4	5
Low	0.25M	7.7	2.7	17	20
Low + PAM	0.25M	7.2	3.4	17	19
Medium	0.50M	8.7	3.4	28	29
Medium + PAM	0.50M	8.5	3.5	34	33
High	0.75M	9.0	3.6	45	40
High + PAM	0.75M	8.9	3.8	44	40

Total carbon %(control soil) = 3.8 (before sowing)
Total nitrogen % (control soil) = 0.28 (before sowing)

Texture

Sand total = 46.8 %
2000----------630µm = 9.0 %
630µm ------200µm = 17.7 %
200µm--------63µm = 20.0 %
Silt----------------------- = 34.1 %
Clay---------------------- = 19.2 %

Textural class

UK classification = Clay loam soil
USDA classification = Loam soil

After harvest

Treatment	$NaHCO_3$ added	pH (H_2O)	EC_e (dSm^{-1})	SAR	ESP	Water stable aggregates (%)
Control	No salt	6.8	1.0	1	1	84
Low	0.25M	8.0	3.4	11	14	62
Low + PAM	0.25M	8.0	3.7	13	16	80
Medium	0.50M	9.0	8.2	34	33	46
Medium + PAM	0.50M	9.0	8.6	32	32	79
High	0.75M	9.0	11.6	46	41	40
High + PAM	0.75M	9.0	11.0	39	37	85

5.6.2 Effects on seedling emergence (%)

The effects of sodicity and PAM on seedling emergence over time are presented in Figures 5.3.1, 5.3.2, 5.3.3 a, b, c, d, e, f, g, h and i and Table 5.3.1. The results revealed

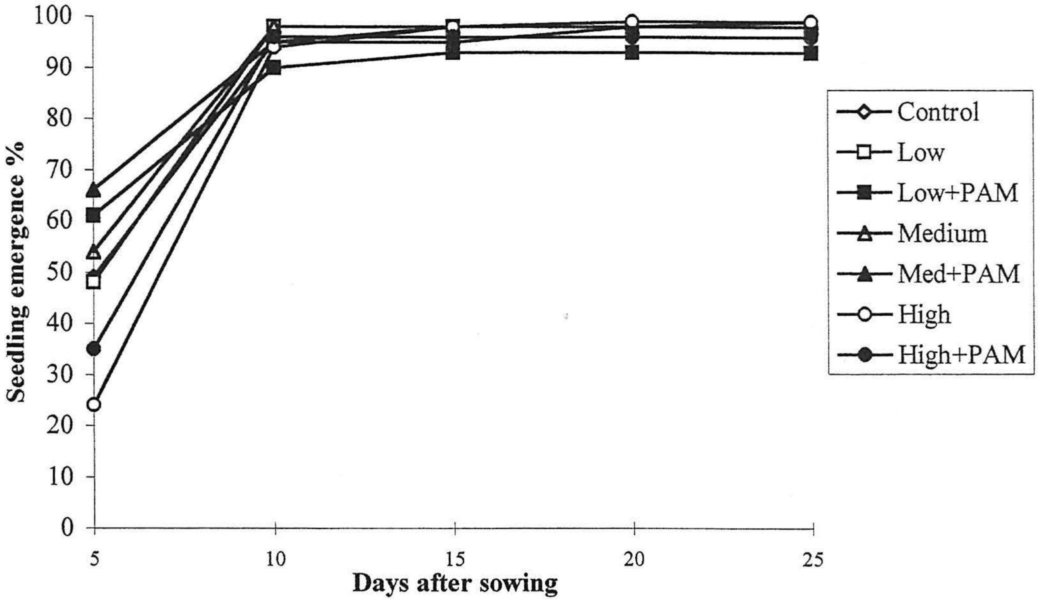


Figure 5.3.1. Main effect of sodicity and PAM on seedling emergence (%) of wheat under clay loam soil condition (data are the average of 10 varieties)

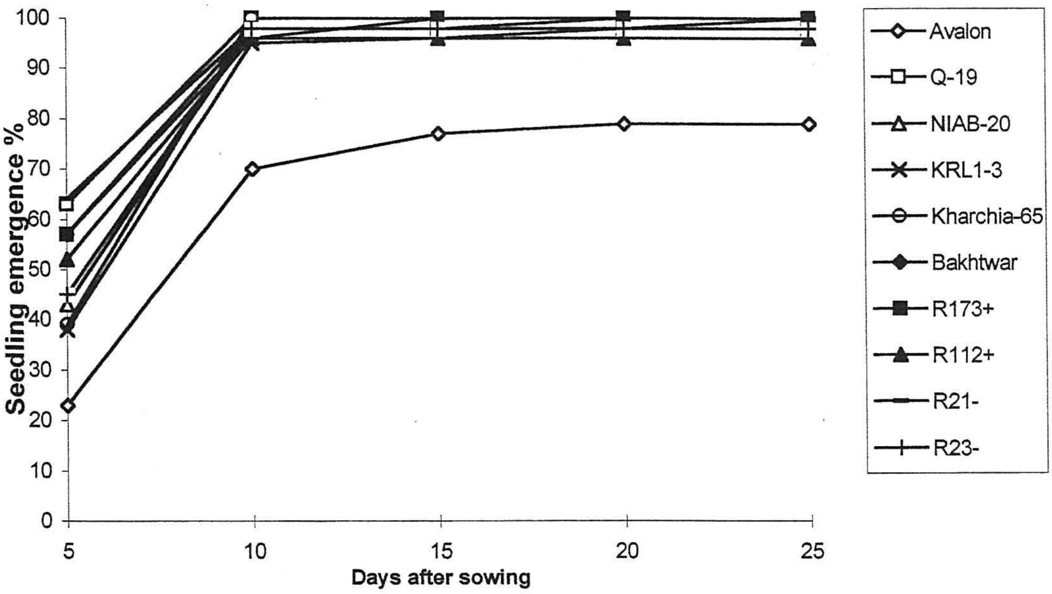


Figure 5.3.2. Effect of varieties on seedling emergence (%) of wheat under clay loam soil condition (data are the average of 7 soil treatments)

that sodicity had no significant effect on the final seedling emergence in clay loam soil. There was no significant difference between low and medium sodicity treatments for seedling emergence. Seedling emergence was greatly decreased at high sodicity at 5 DAS. There was no delay in emergence, in all treatments most of the seedlings had emerged by 10 DAS. In sodic soil conditions emergence of some varieties (Q-19, Kharchia-65, Bakhtwar and NIAB-20) was little affected, sodicity had the largest effects on Avalon. Other varieties and genotypes were intermediate. Soil treatments with PAM resulted in a significant increase in the emergence of almost all varieties except Avalon, which showed a negative response to PAM at high sodicity.

Table 5.3.1. Effect of sodicity and PAM on emergence (%) of 4 durum wheat genotypes and 6 hexaploid wheat varieties recorded at 25 DAS, under clay loam soil condition

	Exchangeable sodium percentage							
	Control	Low		Medium		High		
Variety	5	20	19^{PAM}	29	33^{PAM}	40	40^{PAM}	Means
				Seedling emergence % , 25 DAS				
Durum wheat genotypes								
R173^{+}	100	100	100	100	100	100	100	100.0
R112^{+}	100	100	75	75	100	100	100	96.4
R 21^{-}	100	100	100	100	100	100	100	100.0
R 23^{-}	100	100	88	100	100	100	100	98.2
Hexaploid wheat varieties								
Kharchia- 65	100	100	100	100	100	100	100	100.0
Bakhtwar	100	100	100	100	100	100	100	100.0
NIAB-20	88	100	100	100	100	100	100	98.2
KRL1-3	100	100	100	100	88	100	100	98.2
Q-19	100	100	100	100	100	100	100	100.0
Avalon	88	75	63	100	100	88	63	78.6
Means	97.5	97.5	92.5	97.5	98.7	98.7	96.3	
				Transformed data [arcsine (%/100) values]				
Durum wheat genotypes								
R173^{+}	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.57
R112^{+}	1.57	1.57	1.17	1.17	1.57	1.57	1.57	1.51
R 21^{-}	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.57
R 23^{-}	1.57	1.57	1.37	1.57	1.57	1.57	1.57	1.54
Hexaploid wheat varieties								
Kharchia- 65	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.57
Bakhtwar	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.57
NIAB-20	1.37	1.57	1.57	1.57	1.57	1.57	1.57	1.54
KRL1-3	1.57	1.57	1.57	1.57	1.37	1.57	1.57	1.54
Q-19	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.57
Avalon	1.37	1.17	0.98	1.57	1.57	1.37	0.98	1.23
Means	1.53	1.53	1.45	1.53	1.55	1.55	1.51	

Standered error of the difference between means (S. E. D.) and least significant difference (L. S. D.) for transformed data

	Sodicity	Variety	Var*Sodicity
S. E. D.	0.039	0.047	0.125
L. S. D.	N. S	0.093* * *	N. S

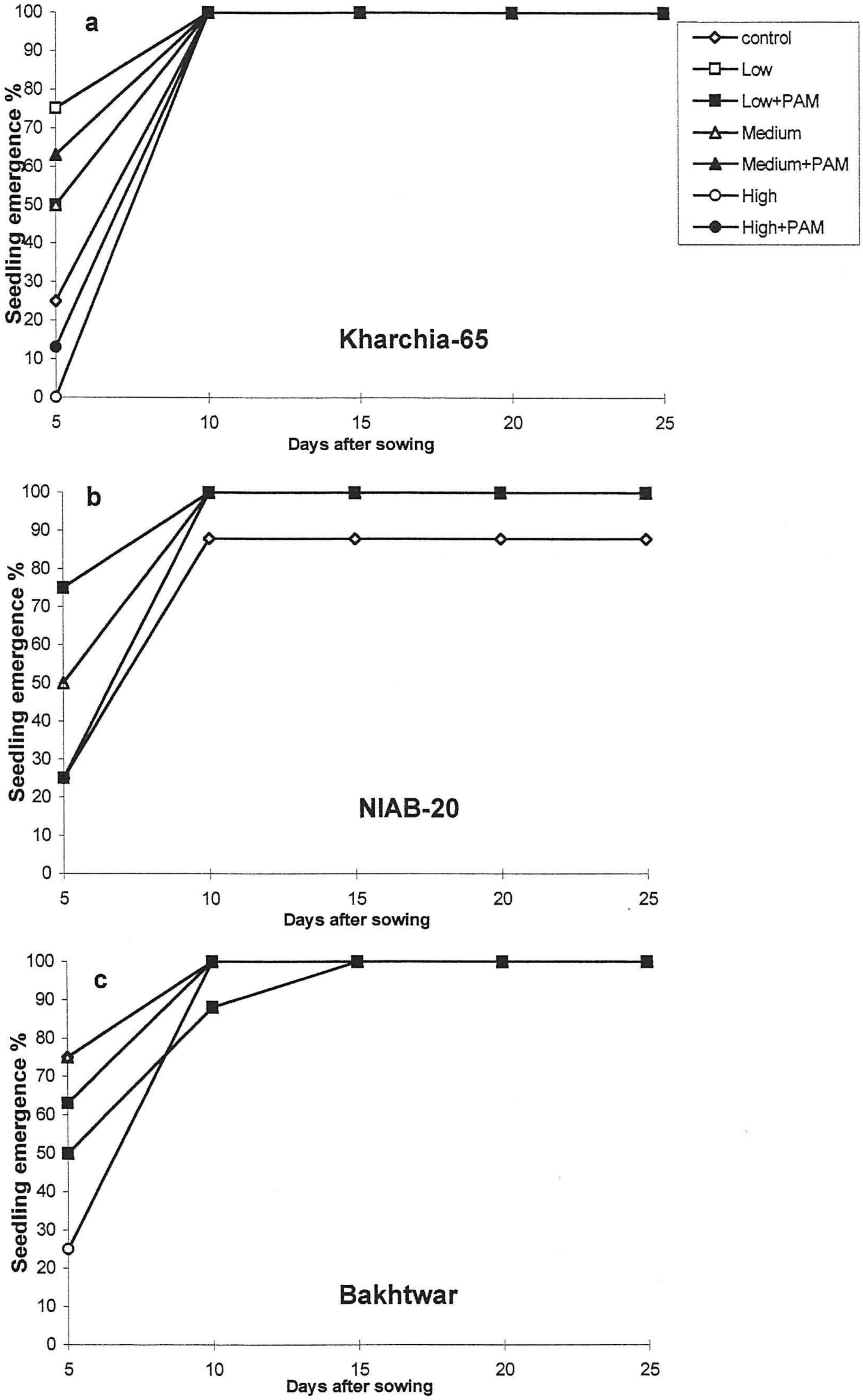


Figure 5.3.3. Effect of sodicity and PAM on seedling emergence of (a) Kharchia-65, (b) NIAB-20 and (c) Bakhtwar under clay loam soil condition

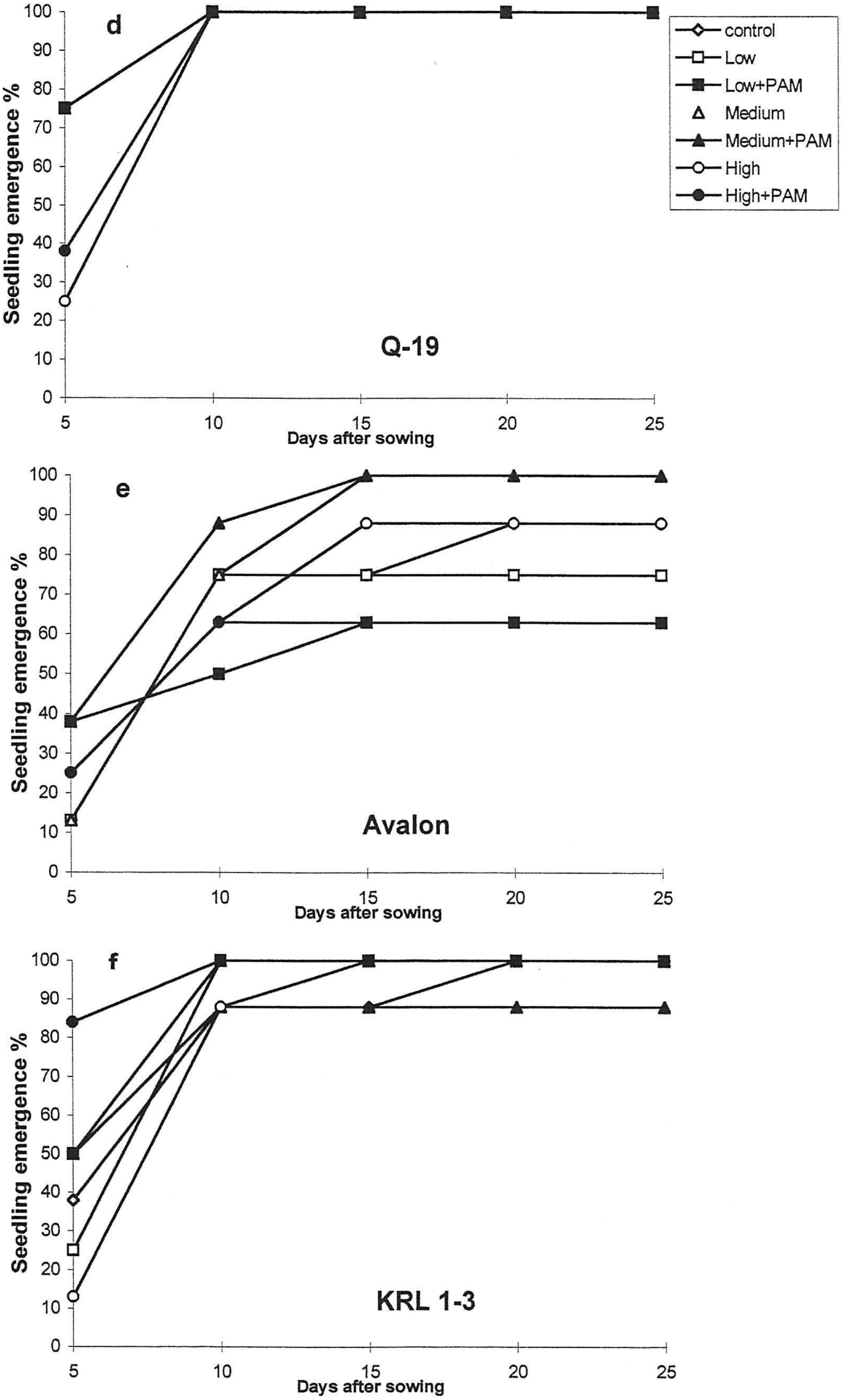


Figure 5.3.3. Effect of sodicity and PAM on seedling emergence of (d) Q-19, (e) Avalon and (f) KRL1-3 under clay loam soil condition.

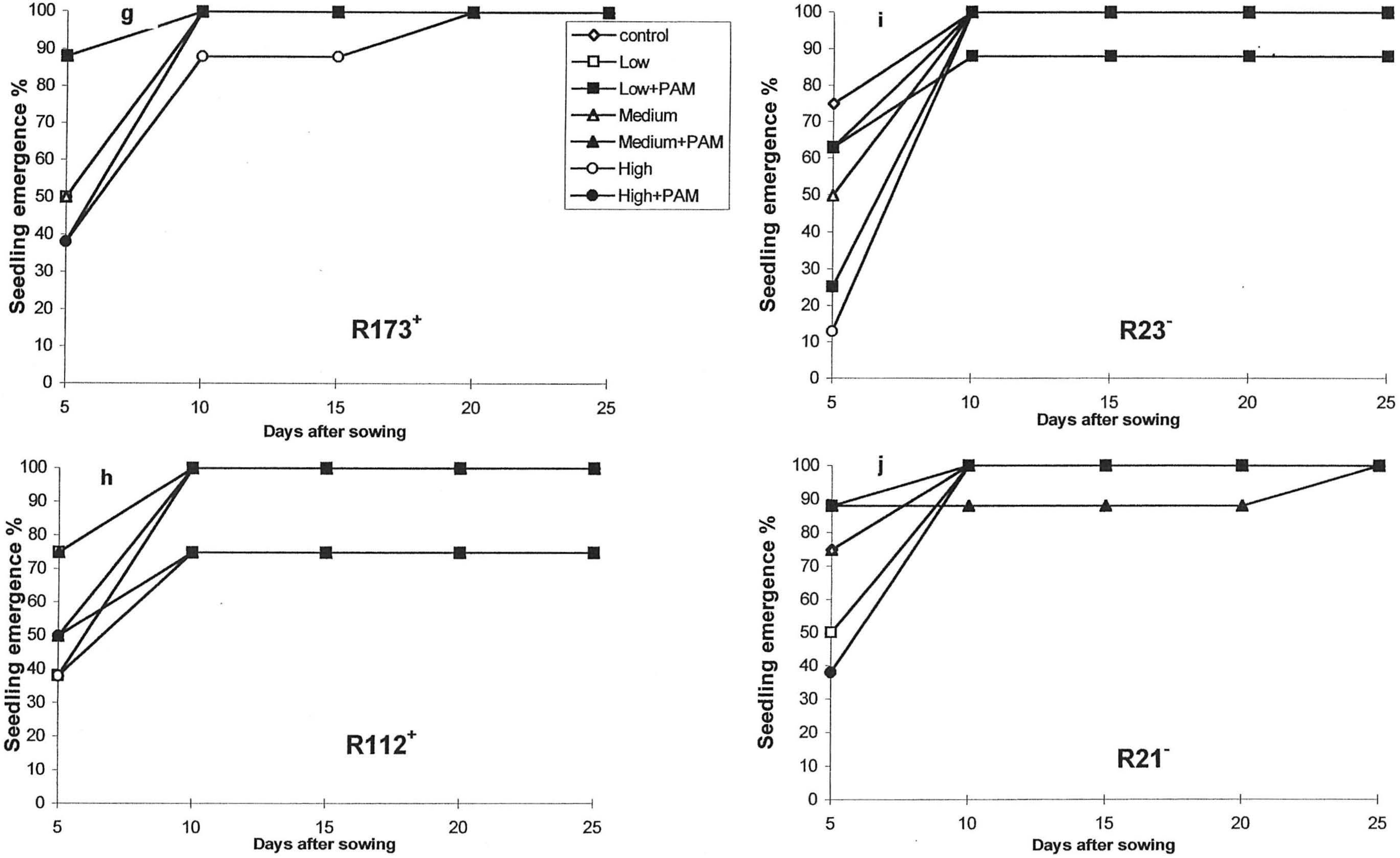


Figure 5.3.3. Effect of sodicity and PAM on seedling emergence of (g) R173$^+$, (h) R112$^+$, (i) R23$^-$ and (j) R21$^-$ durum wheat genotypes under clay loam soil condition

5.6.3 Effects on ion concentration in:

5.6.3(a) Five hexaploid wheat varieties and 1 durum wheat genotype at medium ESP and in medium ESP plus PAM treated soil

Sodicity significantly increased the concentration of Na^+ and significantly decreased the concentration of K^+, Ca^{2+}, Mg^{2+} and K^+/Na^+ ratio in the leaf sap of these varieties (Table 5.3.2a) Treatment of sodic soil with PAM resulted in a marked decrease in Na^+, an increase in K^+ and smaller increases in Ca^{2+}, Mg^{2+} and K^+/Na^+ ratio. These trends were observed for all ions in all varieties except for Mg^{2+} in R173$^+$. The effect of PAM on the concentration of Na^+ was higher in some varieties (Bakhtwar) than in others (KRL 1-3). Though it was not significant, Q-19 and Bakhtwar showed high K^+/Na^+ ratio under sodic conditions in the presence of PAM. All the other varieties showed a slight recovery of Ca^{2+} concentration but it was not significant. Generally R173$^+$ had higher Na^+ and lower K^+ than other varieties tested at medium ESP level.

5.6.3(b) Three durum wheat genotypes and 1 hexaploid wheat variety, at low ESP and in low ESP plus PAM treated soil.

The concentration of Na^+ was significantly increased by sodicity, but the concentrations of K^+ and Ca^{2+} and K^+/Na^+ ratio were significantly decreased (Table 5.3.2 b). PAM significantly decreased Na^+, significantly increased K^+ and resulted in small but non significant increases in Ca^{2+} and K^+/Na^+ ratio. The durum wheat genotypes R21$^-$ and R23$^-$ showed very high Na^+ under sodicity and a significant decrease in Na^+ with PAM. Avalon and R112$^+$ showed a much smaller increase in Na^+ and also a smaller effect of PAM. In all genotypes the concentration of K^+ was significantly lower under sodic condition. With the exception of R21$^-$, all genotypes showed a significant increase of K^+ in sodic soil treatment with PAM. Avalon had the highest K^+/Na^+ ratio, and showed the greatest increase in K^+/Na^+ ratio following treatment of soil with PAM.

Table 5.3.2 (a). Effect of sodicity with and without PAM on the concentrations of Na^+, K^+, Ca^{2+}, Mg^{2+} and K^+/Na^+ ratio extracted from the youngest fully expanded leaf of 6 hexaploid wheat varieties and 1 durum wheat genotype, grown under clay loam soil condition

Ion (mol m^{-3})	ESP	Varieties						
		$R173^+$	KHR-65	NIAB-20	BAKH:	KRL1-3	Q-19	Means
Na^+	5	7	5	4	3	3	3	4.0
	29	280	66	126	123	87	79	126.6
	33+PAM	240	51	109	45	85	52	96.8
	Means	175.4	40.4	79.7	56.7	58.1	44.4	
K^+	5	344	441	308	334	314	289	338.4
	29	98	229	200	179	164	221	181.7
	33+PAM	145	242	216	226	242	286	226.3
	Means	195.7	304.2	241.4	246.4	239.9	265.2	
K^+/Na^+	5	52	92	86	116	128	103	96.4
	29	1	3	2	2	2	3	2.0
	33+PAM	1	5	2	6	3	7	4.1
	Means	17.7	33.7	30.0	41.2	44.5	37.8	
Ca^{2+}	5	51	51	51	86	51	51	56.7
	29	12	10	12	15	15	10	12.0
	33+PAM	16	16	17	17	21	16	17.0
	Means	26.1	25.4	26.6	39.0	28.7	25.7	
Mg^{2+}	5	20	34	17	21	24	20	22.7
	29	16	20	15	16	15	19	16.6
	33+PAM	13	34	22	20	21	23	22.2
	Means	16.3	29.4	18.1	18.9	20.0	20.2	

	Sodicity		Variety		Sodicity*Variety	
	S. E. D	L. S. D	S. E. D	L. S. D	S. E. D	L. S.D
Na^+	13.3	27.0* * *	18.0	36.1* * *	31.0	63.0 * * *
K^+	17.0	35.0* * *	21.4	43.4* * *	37.0	75.2*
K^+/Na^+	4.20	9.00* * *	6.00	12.01* *	10.30	21.00* * *
Ca^{++}	1.7	3.4* * *	2.4	5.0* * *	4.2	8.5* * *
Mg^{++}	1.5	3.0* * *	2.1	4.3* * *	3.1	N. S
Analyses excluding control treatment values						
Na^+	15.4	N. S	26.6	54.1* * *	37.7	N. S
K^+/Na^+	0.50	1.02* * *	0.05	0.10* * *	1.23	N. S

Table 5.3.2 (b). Effect of sodicity with and without PAM on the concentrations of Na^+, K^+ Ca^{2+}, Mg^{2+} and K^+/Na^+ ratio in the sap extracted from youngest fully expanded leaf of 3 durum wheat genotypes and 1 hexaploid wheat variety, grown under clay loam soil condition

Ion (mol m^{-3})	ESP	Genotypes				
		Avalon	R112$^+$	R21$^-$	R23$^-$	Means
Na^+	5	2	7	13	30	12.9
	20	48	84	479	421	257.7
	19+PAM	22	74	332	369	199.3
Means			24.0	54.7	274.5	273.4
K^+	5	327	326	281	254	296.7
	20	191	152	208	31	145.3
	19+PAM	339	318	214	123	248.4
Means		285.4	265.1	234.2	135.8	
K^+/Na^+	5	189.0	50.0	23.0	14.0	68.7
	20	4.0	2.0	0.4	0.1	1.7
	19+PAM	25.0	5.0	1.0	0.3	7.7
Means		72.8	18.9	7.9	4.5	
Ca^{2+}	5	51	63	63	29	51.1
	20	19	33	21	18	22.7
	19+PAM	29	28	39	31	31.7
Means		32.9	41.1	40.7	25.9	
Mg^{2+}	5	23	24	25	18	22.3
	20	28	21	20	17	21.7
	19+PAM	28	22	37	17	25.6
Means		26.4	21.9	27.4	17.2	

	Sodicity		Genotypes		Sodicity*Genotypes	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S.D.
Na^+	11.4	23.0* * *	13.0	27.0* * *	23.0	46.1* * *
K^+	13.0	26.0* * *	15.0	30.0* * *	25.3	51.4* * *
K^+/Na^+	10.00	20.30* * *	12.00	23.40* * *	20.00	41.00* * *
Ca^{2+}	5.3	11.0* * *	6.1	12.4*	11.0	N. S
Mg^{2+}	5.0	N. S	5.4	N. S	9.3	N. S
Analyses excluding control treatment values						
Na^+	13.7	28.3* * *	19.4	40.1* * *	27.4	56.6* *
K^+/Na^+	2.20	4.55*	3.12	6.43* * *	4.41	9.09* *

5.6.4 Effects on growth and development

The effects of sodicity and PAM on the growth and development of wheat are shown in Tables 5.3.4 and 5.3.5. Plant height decreased with increasing sodicity. Seedlings grown at low, medium and high sodicity were shorter than seedlings grown in the control soil. Plants grown at medium and high sodicity with PAM were significantly taller than plants grown without it. The effect of varieties on height was also significant.

Table 5.3.4. Effect of sodicity with and without PAM on height and shoot dry weight of durum wheat genotypes and hexaploid wheat varieties grown under clay loam soil condition and harvested at 58 DAS

	Exchangeable sodium percentage							
	Control	Low		Medium		High		
Variety	5	20	19^{PAM}	29	33^{PAM}	40	40^{PAM}	Means
				Height (cm)				
Durum wheat genotypes								
R173$^+$	51	42	42	35	47	37	41	41.9
R112$^+$	49	46	35	39	43	34	34	39.8
R 21$^-$	51	37	40	33	38	15	30	34.8
R 23$^-$	44	34	35	34	37	19	26	32.5
Hexaploid wheat varieties								
Khar-65	63	58	56	58	69	58	62	60.5
Bakh	48	44	43	41	41	37	39	41.8
NIAB-20	43	43	44	40	43	37	41	42.6
KRL1-3	48	44	44	43	47	40	46	44.5
Q-19	50	44	36	39	49	37	39	41.8
Avalon	34	25	26	25	44	29	20	28.9
Means	47.9	41.6	40.1	38.5	45.6	34.1	37.7	
				Shoot dry wt/plant (mg)				
Durum wheat genotypes								
R173$^+$	437	272	294	138	486	258	221	300.8
R112$^+$	151	266	165	180	323	152	331	224.1
R 21$^-$	337	183	181	118	215	12	78	160.6
R 23$^-$	250	148	129	141	155	15	85	131.8
Hexaploid wheat varieties								
Khar- 65	398	395	368	344	660	318	621	443.5
Bakh	393	264	304	203	314	209	316	286.1
NIAB-20	264	256	238	155	307	272	357	263.9
KRL1-3	229	163	257	156	258	289	396	249.7
Q-19	310	324	363	210	395	167	380	306.9
Avalon	233	70	162	154	276	110	180	169.2
Means	300.2	234.0	246.0	180.0	338.9	180.1	296.5	

		Sodicity	Variety	Var*Sodicity
Height	S. E. D.	1.5	1.8	4.8
	L. S. D.	2.9* * *	3.6* * *	9.5* * *
Shoot dry wt	S. E. D.	27.5	33.0	87.0
	L. S. D.	56.0* * *	67.0* * *	N. S

Kharchia-65 had taller and Avalon had shorter plants than other varieties. In the case of the durum wheat genotypes R173$^+$ and R112$^+$ were taller than R21$^-$ and R23$^-$.

Plant height of some varieties (KRL1-3, NIAB-20, Bakhtwar and Kharcia-65) at both medium and high sodicity with PAM was not significantly lower than that of the control plants. Some other varieties (R173$^+$, Q-19 and Avalon) also showed the same trend but only at medium sodicity with PAM.

Shoot dry weight of seedlings was decreased by 22, 40 and 40% at low, medium and high sodicity respectively compared to the control seedlings. Treatment of soil with PAM increased shoot dry weight more at medium and high sodicity than at low sodicity. Seedlings grown at low, medium and high sodicity with PAM had higher dry weight than seedlings grown at the same sodicity without PAM. Although the variety x sodicity interaction was not significant, shoot dry weight was greatly increased in some varieties (R112$^+$, Kharchia-65, Bakhtwar, NIAB-20, KRL1-3 and Q-19) by PAM at both medium and high sodicity. In some cases the values observed were higher than those in the control plants.

Table 5.3.5 shows the effect of sodicity and PAM on the number of main stem leaves and number of tillers (per plant). Seedlings grown at control, low and medium sodicity had a similar number of main stem leaves, but at high sodicity seedlings had on average fewer leaves than in the control treatment. PAM had no significant effect on the number of main stem leaves. Sodicity had no significant effect on number of main stem leaves for most varieties, but number of main stem leaves was decreased in some varieties (Avalon, R23$^-$, and R21$^-$).

Generally in this experiment seedlings produced few tillers. There were no clear or consistent effects of sodicity or PAM on number of tillers/plant. Averaged overall varieties sodicity resulted in a small decrease in number of tillers /plant. Treatment of sodic soil with PAM increased tiller number at low and medium but not at high sodicity.

Table 5.3.5. Effect of sodicity and PAM on number of fully expanded leaves on the main stem and number of tillers/plant in durum wheat genotypes and hexaploid wheat varieties, grown under clay loam soil condition and harvested at 58 DAS

	Exchangeable sodium percentage							
	Control	Low		Medium		High		
Variety	5	20	19^{PAM}	29	33^{PAM}	40	40^{PAM}	Means
	No. of fully expanded leaves on the main stem/plant							
Durum wheat genotypes								
R173$^+$	5	5	5	5	5	5	5	4.9
R112$^+$	5	5	4	5	5	5	5	4.7
R 21$^-$	5	4	5	4	5	3	4	4.2
R 23$^-$	4	4	4	5	5	2	3	3.8
Hexaploid wheat varieties								
KHR 65	5	5	5	5	5	5	5	5.0
BAKH	5	6	4	5	4	5	5	4.8
NIAB-20	4	5	4	4	5	5	5	4.5
KRL1-3	5	5	5	5	5	5	5	4.9
Q-19	5	5	4	5	6	5	5	5.1
Avalon	4	3	2	3	4	3	3	3.1
Means	4.7	4.5	4.2	4.5	4.9	4.2		4.4
	No. of tillers /plant							
Durum wheat genotypes								
R173$^+$	2	2	2	1	1	0	1	1.2
R112$^+$	1	2	1	1	3	0	0	1.2
R 21$^-$	1	1	1	1	1	0	0	0.8
R 23$^-$	0	1	1	1	1	0	0	0.4
Hexaploid wheat varieties								
Khar- 65	0	0	0	1	1	2	1	0.6
Bakh	0	0	0	0	1	0	0	0.2
NIAB-20	1	0	1	1	2	1	1	0.8
KRL1-3	0	0	0	0	0	0	0	0.0
Q-19	1	0	1	0	1	1	0	0.4
Avalon	1	1	1	1	2	1	0	0.9
Means	0.7	0.6	0.8	0.6	1.1	0.4	0.4	

		Sodicity	Variety	Var*Sodicity
No. leaves/plant	S. E. D.	0.16	0.20	0.52
	L. S. D.	0.33* * *	0.40* * *	1.04* *
No. tillers/plant	S. E. D.	0.14	0.17	0.44
	L. S. D.	0.30* * *	0.33* * *	0.87* * *

5.7 Discussion

5.7.1 Experiment 2

5.7.1.1 Soil

The salt treatments used in this experiment created soils with the required properties (Table 5.1), The addition of the salt mixture (NaCl, $CaCl_2$ and $MgCl_2$) resulted in a higher EC_e (dSm^{-1}) in the saline treatment, confirming the presence of higher concentrations of soluble salts. Although SAR and ESP were slightly increased, the values observed were still within the range of values typical of saline (non- sodic) soils (USSL, 1954; Qureshi and Lennard, 1998).

Conversely in the sodic treatment, following the application of $NaHCO_3$ salt, low EC_e and higher values of pH, SAR and ESP were observed, indicating the adsorption of Na^+ and replacement of other cations from the colloidal complexes and release of HCO^-_3 ions responsible for increasing the soil pH (Rowell, 1994). The low % WSA in the sodic treatment suggested the dispersion of clay and humus colloids (Barzegar *et al.*, 1997). The dark colour shown by the sodic soil, indicated the dissolution, dispersion and upward movement of humus colloids. Other workers (Pearson and Bernstein, 1958; Bains and Fireman, 1964; Sharma, 1991; Choudhary, 1996) have also prepared sodic soils by using the same salt ($NaHCO_3$), and they reported similar types of changes in soil properties. It is noticeable that PAM increased soil aggregation (WSA%) by 92 % compared to the aggregation shown by sodic soil treatment without PAM. The increase in soil aggregation by PAM suggested the preservation of existing aggregates (Cook and Nelson, 1986). Increase in soil aggregation and flocculation by adding polymers in sodic soils has also been reported by other workers including Saleh and Letey (1990).

In general soil chemical properties remained unchanged between sowing and harvest. This was probably due to the short duration of the experiment. However, in the saline treatment there was a marked increase in SAR and ESP. This was possibly due to the precipitation of soluble Ca^{2+} as $CaCO_3$. Formation of sodic soil from saline and saline-sodic soils has been reported by other workers (Qureshi and Lennard, 1998).

Using the classification of salt-affected soils presented by USSL (1954) and Qureshi and Lennard (1998), these soils can be classified as strongly saline and strongly sodic.

The properties of these soils can be compared with the properties of excavated profiles of salt-affected soils in India. Singh *et al.* (1989) surveyed and reported that the salt-affected soils of taluka Chittradurg (district Karnataka, India) had EC_e and pH values ranging from 4.4 to 22.3, and from 8.9 to 9.9 respectively. The ESP values of these soils ranged between 22.9 to 40.4.

5.7.1.2 Seedling emergence

Averaged over all varieties the effects of salinity on emergence were greater than the effects of sodicity. Salinity decreased the seedling emergence at 10 and 20 DAS by 37 and 29 % respectively (Table 5.4). The decreases in emergence % caused by sodicity at 10 and 20 DAS were 32 and 17% respectively. Salinity and sodicity both decreased and delayed emergence (Figure 5.2 and Table 5.1.1). Chhabra *et al.* (1979) also reported that due to the lower availability of water and possibly the direct effect of excess sodium on germinating seeds, high sodicity delays the emergence of crop seeds. Moustafa *et al.* (1966) also concluded that the final germination % of wheat seeds was higher in sodic soil (32-61.8 ESP) than in saline soil with total soluble salts of 1.23-2.4 %.

Averaged over all varieties, treatment of sodic soil with PAM increased seedling emergence % by 15 % compared to the sodic soil treatment without PAM, so that the values observed were similar to those in the untreated control. The increase in seedling emergence % was probably due to increase in soil aggregation. Carr and Greenland (1975) have also presented the similar results.

5.7.1.3 Seedling growth

Salinity and sodicity decreased shoot height by 53 and 73 %, shoot dry weight by 55 and 64 % (Table 5.4) and root length by 48 and 91 % respectively (data not shown). This indicates that in this experiment, under these conditions, the effects of sodicity on growth were greater than the effects of salinity. However, such comparisons must be treated with caution, as the effects observed in such studies depend on the stress levels imposed. Although both salinity and sodicity were high (Qureshi and Lennard, 1998), had different stress levels been tested, different results might have been obtained. The decreases in growth of plants observed may have occurred as a result of any of the factors outlined in the Literature Review (Section 2.2.5). In the case of saline soil these include toxic effects induced by excessive amounts of soluble salts, or an imbalance of nutrients. The decrease in growth and dry matter production in the sodic soil condition may be due to changes in soil physical properties, nutritional disorders related to high pH and impaired metabolism. The greater adverse effects of sodicity than salinity on root growth may be either due to greater accumulation of toxic ions, decreased adsorption of

Table 5.4. Summary table showing the effect of saline and sodic soil with and without PAM treatments on some important parameters of wheat seedlings (- and + indicate per cent decrease and increase over control soil, respectively)

	Soil treatments		
Variety	Saline	Sodic	Sodic +PAM
	Seedling emergence % (10 DAS)		
Kharchia-65	+ 25.0	+ 25.0	+ 25.0
Anmol	- 66.6	- 83.3	- 33.3
NIAB-20	- 62.5	- 37.5	0.0
PAK-81	- 28.6	- 57.1	- 14.2
TW-161	- 37.5	- 50.0	0.0
Bakhtwar	- 62.5	0.0	- 25.0
KTDH-19	- 37.5	- 25.0	- 12.5
SARC-1	- 12.5	- 25.0	0.0
Means	- 36.6	- 31.6	- 8.4
	Seedling emergence % (20 DAS)		
Kharchia-65	0.0	0.0	0.0
Anmol	- 49.3	- 33.3	33.3
NIAB-20	- 50.0	- 12.0	0.0
PAK-81	- 25.0	- 25.0	- 25.0
TW-161	- 37.0	- 50.0	0.0
Bakhtwar	- 37.0	0.0	-12.0
KTDH-19	- 37.0	- 12.0	- 12.0
SARC-1	0.0	0.0	0.0
Means	- 29.4	- 16.5	- 3.2
	Shoot height (cm) (10 DAS)		
Kharchia-65	- 43.7	- 56.3	- 63.0
Anmol	- 81.3	- 81.3	- 68.7
NIAB-20	- 38.5	- 61.5	- 53.8
PAK-81	- 70.6	- 82.4	- 70.6
TW-161	- 76.5	- 94.1	- 64.7
Bakhtwar	- 35.7	- 64.3	- 57.1
KTDH-19	- 35.7	- 64.3	- 64.3
SARC-1	- 15.3	- -61.5	- 53.8
means	- 52.6	- 73.0	- 63.8
	Shoot dry wt /plant (mg) (10 DAS)		
Kharchia-65	- 42.3	- 73.1	- 50.0
Anmol	- 80.9	- 61.9	- 52.4
NIAB-20	- 19.0	- 52.4	- 47.6
PAK-81	- 92.0	- 83.3	- 54.1
TW-161	- 65.4	- 88.5	- 57.7
Bakhtwar	- 56.0	- 52.0	- 64.0
KTDH-19	- 65.6	- 59.4	- 62.5
SARC-1	- 16.6	- 50.0	- 62.5
Means	- 54.6	- 64.4	- 56.7

some essential nutrients, low permeability to air and water, or the dispersed colloidal structure of sodic soils (Toky and Srinivasu, 1995). A larger effect of high exchangeable Na^+ than Ca^{2+} and Mg^{2+} on barley root growth has also been reported by Ratner, (1935). Other authors including Abrol and Bhumbula (1979) and Baykal (1979) have also confirmed that the early seedling stages of wheat are more sensitive to salinity and sodicity than later stages. In the sodic soil treatment most of the seedlings emerged and they grew to a certain height and then gradually turned yellow and withered. Similar types of seedling response have also been observed by Moustafa *et al.* (1966). Pearson and Bernstein (1958) also reported the necrosis and eventual death of barley and wheat seedlings in sodic soils with ESP values in the range of 36 to 60.

As seen from Table 5.4, the treatment of sodic soil with PAM resulted in small increases in shoot height and shoot dry weight. However, the values observed were still markedly lower than those of the control treatment. Despite this small response to PAM, visual observations suggested that plants in the sodic soil treatment had effectively stopped growing, whereas those in the sodic + PAM treatment were still growing, and showed little evidence of chlorosis. Experiments studying the effects of PAM on grain yield of plants grown in sodic soils are reported in Chapters 6, 7 and 8.

5.7.1.4 Varietal response

The experiment tested 11 hexaploid (*Triticum aestivum* L.) wheat varieties (Section 5.3.2.3 and Table 3.1).

The analyses of variance performed on the data showed that there were differences between varieties in the effects of salt treatments on seedling growth but not on seedling emergence. Table 5.4. summarises the % increases or decreases over the control. Differences in response of seedling emergence between varieties should be treated with caution as the variety x salt-treatment interaction was non significant.

The effects of salinity on shoot height and shoot dry weight were greater in 3 varieties (Anmol, PAK-81 and TW-161) than others. The results of this experiment provided no evidence to suggest that varieties that are tolerant of salinity are also tolerant of sodicity. Using shoot dry weight per plant at 20 DAS as an indicator, some varieties (PAK-81, Bakhtwar, KTDH-19 and Anmol) were susceptible to both stresses and showed large decreases. In some varieties (SARC-1 TW-161, NIAB-20 and Kharchia-65) the effects of sodicity were greater than salinity, whereas in others this trend was reversed. This may be a consequence of the high stress levels using in this experiment. Other workers have shown that some varieties that are tolerant of salinity are also tolerant of sodicity eg. Kharchia-65 (Joshi *et al.*, 1982; Chhipa and Lal., 1995). All varieties except Bakhtwar, KTDH-19 and SARC-1 showed a positive response to PAM (a lower % decrease in shoot dry weight per plant). However the response to PAM was greater in some varieties (TW-161, PAK-81 and Kharchia-65) than others (Anmol and NIAB-20).

Anmol, PAK-81 and TW-161 showed poorer performance than the other varieties tested and that places these in the category of salt sensitive. The difference between varieties resulted from saline and sodic soil treatments can be due to genetic variability. Varietal variability in several crops, including barley (Choudhary, 1996) and wheat (Joshi *et al*, 1982; Chhipa and Lal, 1991; Khan *et al.*, 1992) has also been observed under saline and sodic conditions.

5.7.2 Experiments 3 and 4

As both Experiments 3 and 4 tested the same varieties and the sodicity treatments were similar, the results of these experiments are discussed together.

5.7.2.1 Soil

Comparison of Tables 5.2 (page 68) and 5.3 (page 82) shows that the two soils used in Experiments 3 and 4 had generally similar values of pH, EC_e, SAR and ESP, both in the control and in the low and medium sodicity treatments. There were differences between the soils for organic matter and N contents. Due to the dilution of clay loam soil with sand the loamy sand soil used in Experiment 3 had lower organic C and total N % than the clay loam soil used in Experiment 4.

Although there were differences in pH, SAR and ESP between sowing and harvesting time, the values were still in the range of slight to strongly sodic at both stages. The EC_e of $NaHCO_3$ treated soils was also increased compared to the control soil, and it was just above the threshold level (4 dSm^{-1}) considered for non-saline soils (Rowell, 1994), especially at high sodicity. However, although it was higher, EC_e after sowing was still below the level (14-16 dSm^{-1}) considered for 50 % decrease in wheat emergence (Rowell, 1994). Almost all the properties of these soils are comparable to the properties of existing salt-affected soils in Sindh province, Pakistan. Rajpar (1996) found that salt-affected soils of Hyderabad district (Sindh, Pakistan) were variable in texture (Silty clay loam, clay loam and sandy loam) with very low (< 1%) organic matter content and high EC_e in case of saline profiles and high pH, SAR and ESP in case of sodic soil profiles. Chang (1974) noticed the silty clay, clay loam and sandy clay loam texture of soils in the Sanghar district (Sindh Pakistan), where salt-affected soils are also a large problem.

Using the classification of salt-affected soils on the basis of SAR (Qureshi and Lennard, 1998), the low, medium and high ESP treatments of both experiments can be classified as slightly, moderately and strongly sodic respectively. As it was expected, the addition of PAM increased the % WSA in the presence of ESP. Hence the procedures followed created sodic soils with poor and stable soil structure. PAM stabilised the larger soil aggregates with 2-5 mm size. Similar types of larger soil aggregates were also observed in sodic soil using polymers by Martin and Jones (1954).

5.7.2.2 Effects of sodicity

Table 5.4.1 and Figure 5.4 show that the effects of sodicity on emergence, shoot height and shoot dry weight (Figure 5.4) were generally greater at high sodicity than at medium sodicity and greater in loamy sand than in clay loam soil. It appears, therefore, that in clay loam soil, seedlings were not so badly affected by increasing sodicity as they were in loamy sand soil. Differences in the effects of sodicity between soil types are not explained by differences in SAR, ESP, pH and EC_e, as the values of these properties were broadly similar in the corresponding treatments in both experiments (Table 5.2 and Table 5.3). They are also not due to differential environmental conditions as the experiments ran concurrently. The difference in the effects of sodicity could be due to differences in texture and in organic matter content (Tables 5.2 and 5.3). These results can also be compared with those of Barzegar *et al.* (1997), who reported that soil organic matter protects the clay from dispersion, but it depends upon (i) the degree of sodicity (ii) the nature of the organic matter, (iii) clay content and type. In addition there are also some contrasting reports (Oades, 1984), suggesting that greater concentrations of organic anions increase clay dispersion by decreasing the activity of multivalent cations such as Ca^{2+}, and increasing the negative charge on the soil colloids. It has also been reported by Rowell (1994), that the damage caused by sodicity varies between soils. He also reported that the soils with low clay content, soils with kaolinite, mica and smectite clay minerals in association with a high % of sesquioxides are also resistant to sodicity damage. Further more he suggested that the sensitivity of other soils with 2:1 clays depends primarily on clay content. The results obtained from this study indicate greater effect of sodicity on seedlings in loamy sand soil than in clay loam soil. The type of clay was also the same in both experiments, because of the method of soil preparation (Section 5.4.1.1.1). The greater effect of sodicity in loamy sand soil on seedlings was associated with greater Na^+ uptake. Generally seedlings grown in loamy sand soil (Table 5.2.3a and b) accumulated higher concentration of Na^+ and lower concentration of Ca^{2+} than those grown in clay loam soil (Table 5.3.2a and b). Also seedlings in loamy sand soil showed slightly lower K^+/Na^+ ratio than those in clay loam soil.

The results of these experiments showed differences in ion concentration accumulated by the seedlings grown at similar ESP levels. Tables 5.3.2a and b and Tables 5.2.3a and b show that in both soils sodicity increased Na^+, decreased K^+, Ca^{2+} and Mg^{2+} and K^+/Na^+ ratio. The increase in Na^+ and decrease in Ca^{2+} and Mg^{2+} were greater at medium than at low sodicity. However in both soils the decrease in K^+ was greater at low than at medium sodicity. Other workers (Moustafa *et al.*, 1966) have also found similar increases in Na^+ and decreases in other cations with increase in Na^+ saturation in soil.

The improved performance of plants under sodic conditions in clay loam soil, compared with loamy sand soil, was associated with markedly lower leaf Na^+, slightly higher Ca^{2+}, Mg^{2+} and lower K^+ but higher K^+/Na^+ ratio. To the knowledge of author no clear reference was found in the literature describing the ion accumulation in the youngest fully expanded leaf of wheat seedlings in sodic soils with differential texture.

The results of this experiment showed that at equivalent sodicity levels the effects of sodicity on emergence and seedling growth are greater on loamy sand than clay loam soil. The results suggest that this difference is associated with uptake of Na^+. However, it is not clear whether the differences in ion concentration are a consequence or a cause of differences in the effects of sodicity in the two soils. However, Boem and Lavado (1996) reported that direct effects of Na^+ on seedling emergence occurred at SAR values much higher than those which induce clay dispersion. Thus, effects of Na^+ on soil structure may be greater problem than direct effects on seedling emergence.

5.7.2.3 Effects of PAM

The effects of sodicity on final emergence % were larger in Experiment 3. Hence the treatment of sodic soil with PAM had larger effects on final emergence % in loamy sand soil (Experiment 3) than in clay loam soil (Experiment 4). PAM also had beneficial effects on growth of seedlings in loamy sand soil (Tables 5.2.4 and 5.4.1 and Figure 5.4). Except in the low ESP treatment, where the effect of PAM was generally negative, the decreases in shoot height and dry weight were markedly decreased by treatment of sodic soil with PAM.

In the clay loam soil (Tables 5.3.4, 5.4.1 and Figure 5.4), the effects of sodicity were small and hence the effects of PAM were smaller. It is also interesting to note that for some parameters the effect of PAM in clay loam soil was to give higher values than the control. Martin and Jones (1954) found that the effects of a polymer (VAMA) on the growth of carrots in sodic soil was greater at high ESP than low.

Table 5.4.1 Summary table showing the effect of medium and high ESP treatments with and without PAM on emergence and growth of wheat seedlings in two different soils (- and + indicate per cent decrease or increase over control respectively)

ESP	Medium		High	
PAM	-PAM	+PAM	-PAM	+PAM
	Experiment 3 (loamy sand soil)			
Emergence %(5DAS)	-100	- 84	- 90	- 84
(25DAS)	- 15	+3	- 19	- 1
Shoot height (cm)	- 33	- 8	- 72	- 14
	Experiment 4 (clay loam soil)			
Emergence % (5 DAS)	+10	+ 44	- 51	- 37
(25 DAS)	0	+1	+ 1	- 1
Shoot height (cm)	- 20	- 5	- 29	- 21

In both experiments 3 and 4 (Table 5.2.3a,b and Table 5.3.2a,b) the treatment of sodic soil with PAM resulted in a very marked decrease in Na^+ and an increase in K^+/Na^+ ratio, K^+, Ca^{2+} and to some extent Mg^{2+} concentration in the youngest fully expanded leaf of wheat seedlings under both low as well as medium sodic conditions. The effects of PAM on Na^+ and Ca^{2+} were greater on loamy sand soil than on clay loam soil. The decrease in Na^+ ions and increase in nutrient cations (K^+, Ca^{2+} and Mg^{2+}) and K^+/Na^+ ratio in the presence of PAM, indicates the ameliorative action of PAM in sodic soils.

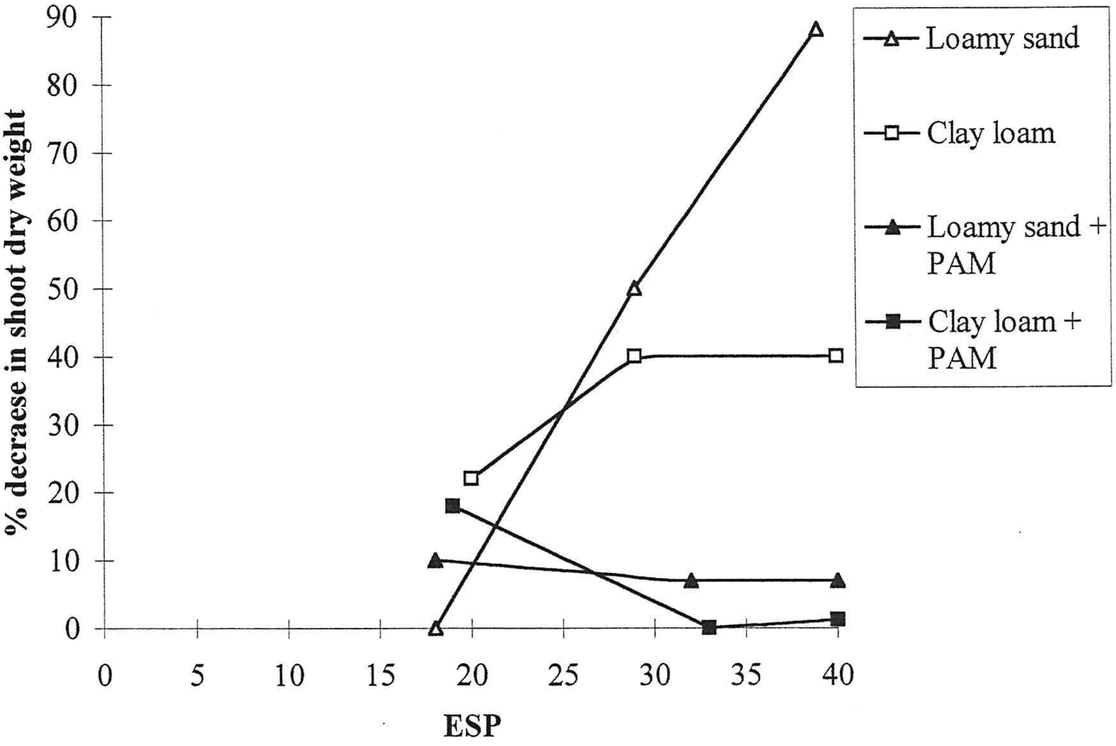


Figure 5.4. Effect of sodicity with and without PAM on the % decrease in shoot dry weight of seedlings grown in two different soils

5.7.2.4 Effect of sodicity and PAM on hexaploid and tetraploid wheats

These two experiments tested 2 types of wheat viz, hexaploid (6 varieties) and tetraploid (4 genotypes). Table 5.4.2 summarises the effects of sodicity and PAM on the hexaploid varieties and tetraploid genotypes.

The effects of sodicity on seedling emergence were broadly similar in the two types of wheat. However for shoot height and dry weight /plant, in both soils and at medium and high ESP, the effects of sodicity were greater on the tetraploid genotypes than on the hexaploid varieties. The large effect of sodicity in tetraploid wheat was probably due to the lack of chromosome 4 D (Gorham *et al.*, 1997). Joshi *et al.* (1982) have also observed similar differences in hexaploid and tetraploid wheat under sodic soil conditions, especially in dry matter production. Sharma (1991) also reported that although most crops are glycophytes, they differ greatly in their capacity to tolerate salts and differences exist between them at species and varietal levels.

It is evident from the data for ion concentrations obtained from both experiments (Table 5.2.3a,b and 5.3.2a,b) that the concentrations of Na^+ were higher, K^+/Na^+ ratio and the concentrations of other cations were lower in tetraploid wheat than in hexaploid wheat, generally in all and especially, in sodic conditions. This indicates that hexaploid wheat absorbs less Na^+ and more K^+ than tetraploid wheat. Gorham *et al.* (1997) and Joshi *et al.* (1982) also presented similar results.

PAM had a marked positive effect on seedling emergence and growth of both types of wheat under both medium and high ESP treatments (Table 5.4.2). However except for emergence, the effect of PAM in both the medium and high sodicity treatments on shoot height and shoot dry weight was generally greater for hexaploid wheat than for tetraploid (durum) wheat in both soils (Table 5.4.2).

Table. 5.4.2. Summary table showing the effects of different ESP levels with and without PAM on seedling emergence %, shoot height and shoot dry weight of hexaploid and tetraploid wheat. (- and + indicate per cent decrease or increase over control respectively)

Soil		Loamy sand soil		Clay loam soil	
Wheat		Hexaploid	Tetraploid	Hexaploid	Tetraploid
ESP					
Seedling emergence % (25 DAS)					
Medium	-PAM	- 14	- 15	+ 4	- 6
	+PAM	+ 7	-3	+ 2	0
High	-PAM	- 20	- 19	+ 2	0
	+PAM	- 2	0	- 2	0
Shoot height					
Medium	- PAM	- 28	- 41	- 14	- 28
	+PAM	+ 4	- 26	+ 2	- 15
High	- PAM	- 69	- 77	- 17	- 46
	+PAM	- 4	- 25	- 14	- 33
Shoot dry weight					
Medium	- PAM	- 33	- 70	- 33	- 51
	+PAM	+ 42	- 52	+ 21	0
High	- PAM	- 83	- 94	- 25	- 63
	+PAM	+ 23	- 39	+ 23	- 39

5.7.2.5 Interaction of varieties/genotypes X sodicity (+ and - PAM)

The results of Experiment 3 (loamy sand soil) (Tables 5.4.3 and 5.4.4) showed that although the interaction of variety x sodicity was not significant in some cases (final emergence in both experiments and shoot dry weight in Experiment 4), generally there were differential responses to high sodicity levels between the genotypes and varieties for the percentage of seedlings emerged, ion uptake, shoot height and shoot dry weight per plant.

Based on seedling emergence Bakhtwar in the hexaploid wheats and R173^{+} in the tetraploid wheats were the most tolerant of all the genotypes tested in these experiments. The least tolerant varieties were Kharchia-65 and Avalon. In the case of tolerance of sodicity the results for Kharchia-65 differ from those obtained in Experiment 2. Other workers have also reported that Kharchia-65 is a salt-resistant wheat variety (Chhipa and

Lal, 1995). Genotypes with a K^+/Na^+ discriminating gene did not give higher emergence than genotypes without this gene (Table 5.4.4). In the case of Experiment 4, sodicity had no effect on final seedling emergence in all tetraploid and hexaploid genotypes (Tables 5.3.1 and 5.4.3 and 5.4.4) and hence there were no differences between varieties.

Based on growth of plants, the data for loamy sand soil (Tables 5.2.4 and 5.4.3), showed that sodicity had adverse effects on the growth of all varieties particularly in the medium and high ESP treatments. In the low ESP treatment many of the tested varieties

Table 5.4.3. Summary table showing the effects of high ESP with and without PAM on emergence %, shoot height and shoot dry weight of hexaploid wheat seedlings in two different soils. (- and + indicate per cent decrease or increase over control respectively)

Soil	Loamy sand soil		Clay loam soil	
ESP	High		High	
Varieties	-PAM	+PAM	-PAM	+PAM
Kharchia-65				
Emergence % (25 DAS)	- 37	- 0	0	0
Shoot height (cm)	- 73	+ 7	- 8	- 2
Shoot dry wt. (mg/p)	- 86	+ 7	- 20	+ 56
Bakhtwar				
Emergence % (25 DAS)	0	+ 14	0	0
Shoot height (cm)	- 68	+ 11	- 23	- 20
Shoot wt. (mg/p)	- 62	+235	- 47	- 20
Niab-20				
Emergence % (25 DAS)	- 12	0	0	0
Shoot height (cm)	- 55	+3	- 14	- 5
Shoot dry wt. (mg/p)	- 89	-14	+ 3	+35
KRL-13				
Emergence % (25 DAS)	- 28	0	0	0
Shoot height (cm)	- 65	+ 21	- 17	- 4
Shoot dry wt. (mg/p)	- 68	+ 85	+26	+ 73
Q19				
Emergence % (25 DAS)	- 12	0	0	0
Shoot height (cm)	- 69	- 5	+26	- 22
Shoot dry wt. (mg/p)	- 92	- 3	- 46	+ 23
Avalon				
Emergence % (25 DAS)	- 33	- 49	0	- 28
Shoot height (cm)	- 81	- 76	- 15	- 41
Shoot dry wt. (mg/p)	- 75	- 6	- 53	- 23

showed slightly improved growth compared to the control. It is also evident from these results, that the relative effects of sodicity on the different varieties were not consistent in Experiments 3 and 4. Decrease in shoot dry weight/plant in response to high sodicity was greatest in Q-19, NIAB-20 and Kharchia-65 in Experiment 3, but in Experiment 4 greatest decrease was observed in Avalon, Bakhtwar and Q-19. Bakhtwar and KRL1-3 were the most tolerant varieties in Experiment 3, but KRL 1-3, NIAB-20 and Kharchia-65 were the most tolerant varieties in Experiment 4. The results provided no evidence indicating that varietal differences in the effects of sodicity on shoot dry weight/plant were related to varietal differences in leaf Na^+. Bakhtwar and KRL 1-3 showed the lowest decreases in shoot dry weight/plant, but these varieties had higher leaf Na^+ than Q-19, which showed highest decrease in shoot dry weight in both experiments. On the basis of comparison of varieties in the sodic soil treatment, Avalon was the most sensitive variety, because it had the lowest shoot dry weight/plant under all soil treatments. However, when compared to the control, Avalon showed a low % decrease, as shoot dry weight was low in the control.

In both soils, sodicity at all ESP (low, medium and high) levels had larger effects in the growth of $R21^-$ and $R23^-$ than $R173^+$ and $R112^+$ (Tables 5.2.4, 5.3.4 and 5.4.4), possibly due to the effect of the K^+/Na^+ ratio discriminating character in $R173^+$ and $R112^+$ (Gorham *et al.*, 1997). The two genotypes without the K^+/Na^+ discriminating gene ($R21^-$ and $R23^-$) had higher Na^+ and lower K^+ and K^+/Na^+ ratio than the genotypes with gene ($R112^+$ and $R173^+$) (Tables 5.2.3a and b). Among the genotypes with the gene, $R173^+$ showed higher uptake of Na^+ on both soils than $R112^+$. However this difference must be treated with caution as ion uptake was measured at two sodicity levels. The trends of Na^+ uptake shown by these genotypes in the clay loam soil were similar to those observed in the loamy sand soil. This suggests that due to the difference in soils the trend of ion uptake cannot be changed but concentration may vary with soil.

The results presented in Table 5.4.3 indicate that in Experiment 3 PAM improved the performance of almost all and in some varieties (Bakhtwar and KRL1-3) plants in the high sodicity with PAM treatment had higher shoot dry weight than in the control. Similarly with the exception of two varieties (Avalon and Bakhtwar) the effect of PAM, was greater in all varieties in Experiment 4.

Table 5.4.4 Summary table showing the effects of high ESP with and without PAM on seedling emergence %, shoot height and shoot dry weight of durum wheat genotypes in two different soils. (- and + indicate per cent decrease or increase over control respectively)

Soil	Loamy sand soil		Clay loam soil	
ESP	High		High	
Genotypes	-PAM	+PAM	-PAM	+PAM
R173$^+$				
Emergence % (25DAS)	0	0	0	0
Shoot height (cm)	- 77	- 19	- 28	- 20
Shoot dry wt (mg/p)	- 95	- 38	- 41	- 49
R112$^+$				
Emergence % (25 DAS)	- 25	0	0	0
Shoot height (cm)	- 69	- 8	- 31	- 31
Shoot dry wt. (mg/p)	- 91	+19	+ 1	+119
R21$^-$				
Emergence % (25 DAS)	- 37	0	0	0
Shoot height (cm)	- 83	- 34	- 71	- 41
Shoot dry wt. (mg/p)	- 96	- 54	- 96	- 77
R23$^-$				
Emergence % (25 DAS)	- 12	- 0	0	0
Shoot height (cm)	- 79	- 40	- 57	- 41
Shoot dry wt. (mg/p)	- 94	- 70	- 94	- 66

However, although PAM had an effect on growth of almost all genotypes, the effect of PAM was greater on the genotypes with the K^+/Na^+ discriminating gene than without gene (Table 5.4.4).

It can be observed from the results presented in Tables 5.2.3a and b and 5.3.2 a and b), that the use of PAM was effective in ion uptake by all varieties and genotypes in both soils. Although the effect of PAM was slightly higher in some varieties and lower in others, generally both durum wheat genotypes and hexaploid wheat varieties accumulated less Na^+, more K^+, Ca^{2+} and Mg^{2+} and they showed higher K^+/Na^+ ratio in presence of PAM than in absence. Amongst the durum wheat genotypes, R112$^+$ showed the highest response to PAM, followed by R21$^-$ and R23$^-$. R173$^+$ responded to PAM in loamy sand soil but not in clay loam soil.

5.8 Other possible effects of polymers on soil properties

The improvements in plant performance obtained by using PAM in sodic soils were largely associated with increased WSA% and hence improved soil structure. However, as PAM is an anionic polymer it may also have served as an organic colloid. Hence it may also have increased the cation exchange capacity and water holding capacity of the soil. Although PAM is an amide, and hence theoretically it may also have increased soil N supply, its N content was found to be small (3.5%). Any such effects would have been observed if PAM had been applied to the control (non-sodic) soil.

5.9 Conclusions

- Sodicity decreased seedling emergence in loamy sand and clay loam soil with low organic matter and N, but not in clay loam soil with more organic matter and N.
- As sodicity increased leaf Na^+ increased, K^+, K^+/Na^+ ratio and Ca^{2+} decreased. Trends in uptake were the same in both clay loam and loamy sand soils.
- PAM increased emergence and growth and decreased Na^+, and increased K^+ and K^+/Na^+ ratio.
- Varieties responded differentially to PAM as well as to sodicity. Tetraploid (durum) wheat was more sensitive to sodicity than hexaploid wheat. In tetraploid wheat, genotypes without the Kna1 gene were more sensitive than those with the Kna1 gene. These results should be treated cautiously as they are based on single replicate pot, hence in Chapter 10 growth and yield of these genotypes were tested using 4 replicates.

CHAPTER 6

Effect of different ESP levels and PAM on the growth, ion uptake and yield of Kharchia-65 wheat variety

CHAPTER 6

Effect of different ESP levels and PAM on the growth, ion uptake and yield of Kharchia-65 wheat variety

6.1 Introduction

In the earlier experiments (Chapter 5), PAM resulted in increased emergence, growth, nutrient cations (K^+ and Ca^{2+}) including K^+/Na^+ ratio and decreased the uptake of Na^+ by seedlings in the presence of sodicity. However, that study was only up to the seedling stage and it was concluded that further tests were required to ascertain the effects on yield. As it is already mentioned in Chapter 5, the decrease in plant growth in sodic soils can be caused by high sodium concentrations or poor soil structure or by both. What direct influence the level of exchangeable sodium has on plant growth, ion uptake and grain yield is not very well known. All that is known is that in some cases, nutrient availability or direct sodium toxicity may limit growth and yield but, for many crops under sodic soil conditions, poor soil structure is one of the principal limiting factors. Use of soil conditioners that aggregate soil in the presence of exchangeable sodium offers a means of evaluating these two effects (Allison and Moore, 1956 Bernstein and Pearson, 1956). At an equal ESP level the yield of some crops can be improved by polymers, if properly applied. However, that also depends upon the sensitivity of plants to exchangeable sodium. Wheat and barley yield can be improved by applying polymer at high ESP level. However, yield of oat plants was only slightly increased by maintaining the soil structure with polymers, because of it's great sensitivity to exchangeable sodium (Pearson and Bernstein, 1958).

It has been shown by some workers that the salt resistant variety Kharchia-65 can perform well in sodic soil conditions (Joshi *et al.*, 1982; Sharma, 1991). However it is not known whether this can be attributed to poor soil structure or high exchangeable sodium in sodic soil conditions.

This study was thus conducted to examine the effects of exchangeable sodium in the presence of poor and stable soil structure on a salt-resistant wheat variety.

6.2 Objectives

The objectives of the work reported in this Chapter were:

(1).To investigate the effects of sodicity on growth, ion uptake and yield of a salt resistant wheat variety;

(2). To investigate the effects of PAM on soil physical and chemical properties;

(3). To determine if application of PAM decreases the adverse effects of sodicity on ion uptake, growth and yield;

(4). To quantify the physical and chemical effects of sodicity on wheat growth and yield.

6.3 Materials and Methods

6.3.1 Soil preparation

6.3.1.1 Sodic soils

Sodic soil was prepared using soil collected from the experimental area of Henfaes Agricultural Research Station, University of Wales, Bangor. In order to generate low, medium and high ESP levels, 3 lots of soil (90.5 kg / lot) were sprayed with 0.25M, 0.5M and 0.75M $NaHCO_3$ salt solution respectively. The procedure of spraying, raking and drying etc. is described in Chapter 3 (Section 3.1.1).

6.3.1.2 PAM application

After the attainment of the desired sodicity levels, half (45.25 kg) of the soil of each lot with low, medium and high ESP levels was sprayed with anionic PAM soil conditioner @ 0.2 kg/100 kg soil, using a knapsack sprayer. The PAM treated soils were allowed to air dry (Section 3.1.1). After drying, soils were placed in round plastic buckets of 6 kg capacity with drainage holes in the base. These buckets were placed on a wooden bench in a randomised block design.

6.3.2 Growth conditions and treatments

The experiment was conducted in a glasshouse at the Henfaes Agricultural Research Station, University of Wales, Bangor during summer 1997. Temperature in the glasshouse was not controlled and no supplementary lighting was used for this study.

The minimum and maximum temperature of the glasshouse is shown in Appendix 1. There were eight replicates of each of the seven treatments (control, low ESP, low ESP plus PAM, medium ESP, medium ESP plus PAM, high ESP and high ESP plus PAM).

6.3.3 Sowing and plant growth

Twenty seeds of the Indian salt-resistant wheat variety Kharchia-65 (Table 3.1) were sown in each bucket on 23 May 1997. Two seeds were placed in each position with 4 centimetres plant to plant and row to row distance. Thirteen days after sowing seedlings were thinned to 10 uniform plants per pot. The exception was the high ESP without polymer treatment, where the number of plants per pot was not uniform due to the lower survival. To afford uniform fertility in all pots fertiliser Phostrogen (See Section 4.3.4) was applied @ 0.5 grams/l of soil to each pot three times; at the time of sowing, 15 days after sowing and 45 days after sowing. Irrigation water was applied as required.

6.3.4 Leaf sampling and chemical analysis of sap

Forty days after sowing, the fully expanded flag leaves of three plants from each replicate of each treatment were sampled. The three leaves were combined, placed in Eppendorf tubes and stored at -10 °C in a freezer. These plants were also used to record plant height (to the tip of the longest leaf), number of fully expanded leaves on the main stem and number of tillers per plant. The plants were allowed to grow up to maturity. Frozen flag leaves were crushed and sap was extracted and analysed to determine Na^+, K^+, Ca^{2+}, and Mg^{2+} by following the methods described in Chapter 3 (Section 3.2).

6.3.4 Final harvest

At maturity (83 DAS) all plants were harvested by cutting at soil level. The three plants which were used for chemical analysis and the plants without ears were not incorporated in the yield data. The remaining surviving plants with ears from each treatment were used to record number of heads per plant. The ears were separated; straw and ears were placed in separate paper bags, oven dried (for 48 hours at 82 °C) and their dry weight was recorded. Threshing was done by hand. Grain dry weight in grams and number of grains per plant were recorded. Plant survival % was calculated using the formula:

$$\text{Survival \%} = \frac{\text{Plants survived with ears at maturity x 100}}{\text{Total plants per pot (7)}}$$

6.3.6 Preparation of grain and straw samples and chemical analyses

Grain and straw samples from four replicates of each of the control, medium and high ESP treatments with and without PAM were prepared for chemical analysis (N, Na^+, K^+, Ca^{2+}, Mg^{2+}, Zn^{2+}, Cu^{2+}, Mn^{2+} and Fe^{2+}) by following the methods shown in Chapter 3, section 3.2.

6.3.7 Soil analyses and calculations

The soil of this experiment was analysed before sowing and after harvesting of the plants. A single composite sample before sowing was analysed for texture, pH, EC_e, soluble Na^+, K^+, Ca^{2+}, and Mg^{2+} (mmol l^{-1}). ESP and SAR were calculated from the Na^+, Ca^{2+} and Mg^{2+} concentrations (mmol l^{-1}) in saturation extracts (Rowell, 1994). The soil samples which were taken at the end of the study from each bucket of each treatment were analysed individually to record the water stable aggregate %, Na^+, K^+, Ca^{2+} and Mg^{2+} and to calculate the SAR and ESP. The procedures for soil analyses and calculations are shown in Chapter 3 (Sections 3.1.1 and 3.1.2).

6.3.8 Statistical analyses

The results were analysed statistically by analysis of variance using Minitab statistical package. At the highest ESP in some pots there were no plants. Hence the results were analysed in two ways.

Data for yield per plant were analysed using the data for all replicates, including zero yield for replicates in which all plants died. The standard error of the differences between means were calculated by using the formula S. E. D. = $\sqrt{2 * EMS / n}$ (See Section 4.3.7).

At high sodicity some plants died and hence were unavailable for sap extraction for ion analysis. Hence in this case the analysis of variance were computed with an unequal number of replications. In this case the standard error for the differences between means and least significant difference for chemical analysis were calculated by the formula:

S. E. D. = $\sqrt{(1/r_i + 1/r_j)EMS}$

L. S. D. = $\sqrt{(1/r_i + 1/r_j)EMS}$ * t (0.05) df (Gomez and Gomez, 1984)

where:

r_i = replications with incomplete n and

r_j = replications with complete n

t (0.05) df = value from the t distribution table at 5% probability level and error degrees of freedom.

Due to the larger differences in the values of Na^+ and K^+/Na^+ ratio between the control and sodic treatments, separate analyses were performed on Na^+ and K^+/Na^+ ratio data by excluding the control treatment data.

6.4 Results

6.4.1 Soil characteristics

The properties of the soil before sowing and after harvesting are shown in Table 6.1. The values are for a single before sowing and the means of 8 samples after harvest from each treatment. The data show that although, the electrical conductance of the saturated paste extracts (EC_e) increased with increase in the concentration of $NaHCO_3$ added, the values were still in the range traditionally associated with non saline soils.

The data also showed that soil pH, SAR and ESP increased with increasing concentration of $NaHCO_3$ salt. Hence the pH, SAR and ESP of the medium and high ESP treatments (with and without PAM) were typical of naturally occurring sodic soils. Generally the effects of PAM on soil properties before sowing were very slight.

The soil showed slight changes in chemical properties during the course of the experiment. The electrical conductivity was slightly higher in the high sodicity treatment, but the pH was lower in almost all sodic treatments compared to the before sowing values shown by these same treatments. In the absence of PAM, ESP generally decreased between sowing and harvest in the low and medium ESP treatments, and in the high ESP and PAM treatment.

There was a consistent decrease in the percentage of water stable aggregates (WSA%) with increasing concentration of NaHCO$_3$.

Treatment of soil with PAM decreased ESP and SAR and increased WSA% after harvest, especially in the medium and high ESP treatments. At harvest the % WSA in the treatments with PAM were greater than the values of the control.

Table 6.1. Electrical conductivity (EC$_e$), pH, sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), % water stable aggregates (% WSA) of the soil before sowing and after harvest

Before sowing

	Treatments						
Sodicity	Control	Low	Low^{PAM}	Med	Med^{PAM}	High	High^{PAM}
NaHCO$_3$	no	0.25 M		0.5 M		0.75 M	
EC$_e$ (dSm^{-1})	2.7	2.7	2.7	4.2	4.0	6.0	5.2
pH (1:2.5)	6.3	7.5	7.5	8.2	8.0	8.8	8.7
SAR	2.0	13.0	12.3	27.9	26.9	52.6	57.1
ESP	1.7	15.4	14.7	28.9	28.2	43.7	45.8

after harvest

	Treatments						
Sodicity level	C	Low	Low^{PAM}	Med	Med^{PAM}	High	High^{PAM}
EC$_e$ (dS/m)	1.8	3.0	2.9	4.1	4.1	8.7	6.1
S. E.	± 0.11	± 0.26	± 0.16	± 0.30	± 0.32	± 0.73	± 0.43
pH (1:2.5)	6.2	6.9	6.8	7.0	6.6	7.3	7.0
S. E.	± 0.06	± 0.01	± 0.07	± 0.05	± 0.05	± 0.05	± 0.05
SAR	0.95	13.7	11.7	34.7	26.9	59.6	42.9
S. E.	± 0.07	± 1.5	± 0.5	± 2.3	± 1.1	± 3.7	± 3.6
ESP	<0.01	8.5	8.4	16.5	14.0	46.6	38.2
S. E.	± 1.1	± 1.6	± 0.5	± 1.4	± 0.9	± 1.6	± 2.2
WSA %	60	48	88	36	80	29	75

Texture = Clay loam (UK classification)

6.4.2 Effects on survival %

Table 6.2 shows the effects of different ESP levels and PAM on survival %, at maturity height , number of fully expanded leaves on the main stem and number of tillers per plant at 40 DAS. Survival percentage of plants was not significantly affected by sodicity at low and medium ESP levels. However, at high ESP level survival percentage was significantly lower than in the control, but significantly increased by PAM. Survival of plants was increased more by PAM at high ESP level than at medium ESP level.

6.4.3 Effects on growth and development at 40 DAS

Plant height decreased with increasing level of sodicity. At high ESP level plants were much shorter than in the control and at low and medium ESP levels. The plants grown in presence of PAM were taller than the plants grown in absence of PAM at all sodicity levels. However, the effect of PAM was significant at high and medium but not at low ESP levels.

Table 6.2. Effect of different ESP levels and polyacrylamide on plant survival % at maturity, height, number of fully expanded leaves on the main stem and number of tillers per plant at flag leaf stage (40 DAS) of Kharchia-65, grown in sodic soils

	Exchangeable sodium percentage at sowing						
Sodicity level	Control	Low		Medium		High	
	2	15	15^{+}PAM	29	28^{+} PAM	44	46^{+} PAM
Parameter							
Plant survival % (with ears)	80.4	75.0	75.0	80.4	83.9	23.2	67.9
Height (cm)	78.0	59.8	65.3	52.1	60.5	21.5	44.3
No of fully expanded leaves	6	7	7	6	6	4	6
No of tillers /plant	0.1	0.3	0.2	0.2	0.5	0.0	0.3

	S. E. D.	L. S. D.
Plant survival %	10.94	22.65* * *
Height (cm)	3.77	7.81* * *
No of fully expanded leaves	0.4	0.8 * * *
No of tillers /plant	0.18	N. S

There were fewer leaves on the main stem in the plants grown at high ESP level than the plants grown at other soil treatments. Application of PAM increased the number of fully expanded leaves on the main stem at high ESP level. At low ESP level more leaves were recorded than in the control and at medium ESP levels. PAM had no positive or negative effect at low and medium ESP levels. Low tiller production was recorded in this experiment. The plants grown at control, low and medium ESP levels had few tillers, while the plants at high sodicity level had no tillers at all. At medium and high ESP levels some of the plants in the treatments with PAM produced tillers.

6.4.4 Effects on ion accumulation and K^+/Na^+ ratio in flag leaf sap

Table 6.3. shows the effects of different ESP levels and PAM on the concentrations of Na^+, K^+, Ca^{2+}, Mg^{2+} and K^+/Na^+ ratio in the flag leaf sap of Kharchia-65. There are several S. E. D. and L. S. D. values for different comparisons in this data, due to uneven replications as a result of death of plants at high sodicity.

Plants grown at medium and high ESP had significantly higher Na^+ than the plants grown in the control and at low ESP. Although an equal amount of Na^+ was added in the treatments of soil with PAM and without PAM, at medium and high ESP, the concentration of Na^+ in the plants grown with PAM was significantly lower than in the plants grown without PAM.

The K^+ concentration at low and medium ESP was significantly higher than in the control. In the absence of PAM and at high ESP, K^+ was lower than at low and medium ESP and lower than in the control. At high ESP, addition of PAM resulted in a significant increase in K^+, to values similar to those observed at low and medium ESP.

With increasing level of sodicity; K^+/Na^+ ratio decreased progressively. Plants grown in the control and at low ESP had higher K^+/Na^+ ratio than the plants grown at medium and high ESP. Treatment of soil with PAM resulted in a significant decrease in K^+/Na^+ ratio at low ESP, and small but not significant increase in K^+/Na^+ ratio at high sodicity.

Sodicity resulted in a significant decrease in Ca^{2+} concentration and the plants grown at high ESP level had a very low Ca^{2+} concentration. The effect of PAM on the concentration of Ca^{2+} was not significant at any sodicity level. Sodicity and PAM had no significant effects on Mg^{2+} concentration in the leaf sap. However, the concentration was slightly lower at high ESP and high ESP with PAM treatments, compared to all other soil treatments.

Table 6.3. Effect of different ESP levels and polyacrylamide on the concentrations of Na^+, K^+, Ca^{2+}, Mg^{2+} and K^+/Na^+ ratio in the flag leaf sap of Kharchia- 65, grown in sodic soil.

	Exchangeable sodium percentage at sowing						
Sodicity level	Control	Low		Medium		High	
Ions (mol m^{-3})	2	15	15+PAM	29	28+ PAM	44	46+ PAM
Na^+	2.7	3.8	4.5	52.2	38.1	115.2	68.1
K^+	178.0	224.0	220.0	226.0	224.0	143.0	201.0
K^+/Na^+	66.9	60.1	51.7	4.6	6.4	1.3	2.9
Ca^{2+}	13.9	7.0	7.9	7.1	6.6	3.5	4.2
Mg^{2+}	13.6	13.7	14.1	14.4	13.6	12.3	12.4

	Equal replications		Unequal replications				Significance level		
	S. E. D^1	L. S. D^1	S. E. D^2	L. S. D^2	S. E. D^3	L. S. D^3	S. E. D^4	L. S. D^4	
Na^+	4.58	9.20	6.2	12.5	4.7	9.5	6.3	12.6	* * *
K^+	5.89	11.95	8.0	16.1	6.2	12.4	8.2	16.5	* * *
K^+/Na^+	3.25	6.56	4.4	8.9	3.4	6.8	4.5	9.0	* * *
Ca^{2+}	0.61	1.23	0.7	1.4	0.6	1.3	0.9	1.7	* * *
Mg^{2+}	0.71	N. S	1.0	N. S	0.7	N. S	1.0	N. S	N. S
Analyses excluding control treatment values									
Na^+	5.10	10.16	7.6	15.5	5.2	10.5	6.9	14.0	* * *
K^+/Na^+	3.06	6.21	4.7	9.5	3.2	6.4	4.2	8.6	* * *

L. S. D^1 = for comparison between control, low, low plus PAM, medium and medium plus PAM treatments.

L. S. D^2 = for comparison between high ESP and all other treatments excluding high ESP plus PAM treatment.

L. S. D^3 = for comparison of high ESP plus PAM with other soil treatments excluding high ESP treatment.

L. S. D^4 = For comparison between high ESP and high ESP plus PAM treatments.

6.4.5 Effects on yield and yield components

Table 6.4. shows the effects of different ESP levels and PAM on grain yield and yield components. At the highest level tested, sodicity resulted in a significant decrease in a grain yield, yield components and all other traits recorded at harvest. Grain yield per plant decreased with increasing sodicity levels. The decrease at high ESP was higher than that at low and medium ESP levels. Grain yield was increased by PAM in all sodicity treatments. The effect of PAM on grain yield increased with increase in sodicity level. The increase was not significant at low and medium ESP, but it was significant at high ESP.

Table 6.4. Effects of different ESP levels and polyacrylamide (PAM) on grain and straw yield and yield components

	Exchangeable sodium percentage at sowing						
Sodicity level	Control	Low		Medium		High	
	2	15	$15^{+\text{PAM}}$	29	$28^{+\text{PAM}}$	44	$46^{+\text{PAM}}$
Parameters							
Grain yield per plant (mg)	549.2	470.4	475.0	410.0	474.5	110.0	412.5
Grains per plant	15.5	13.2	13.2	11.9	12.9	4.9	14.2
1000 grain wt (g)	35.4	35.2	35.5	34.6	36.2	7.9	29.0
Straw wt (mg/plant)	739.7	606.7	677.7	480.2	533.8	136.8	516.0
Harvest index (%)	42.4	43.6	40.6	46.4	46.3	15.7	46.4
Heads per plant	1.0	1.0	1.0	1.0	1.0	0.4	1.0
Plants survived with ears/m^2	502	469	469	502	525	145	424
Grain yield (g/m^2)	279	224	217	211	246	50	140
Straw yield (g/m^2)	374	288	318	246	280	48	156

	S. E. D.	L. S. D.
Grain yield (mg/plant)	79.88	165.36* * *
Grains per plant	2.46	5.10 * *
1000 grain wt (grams)	2.78	5.78 * * *
Straw wt (mg/plant)	110.90	229.56 * * *
Heads per plant	0.03	0.06 * * *
Harvest index (%)	5.05	10.45 * * *
Grain yield (g/m^2)	42.15	87.25 * * *
Straw yield (g/m^2)	40.32	83.46 * * *
Plants survived with ears/m^2	68.38	136.76 * * *

A similar trend of decrease with increasing sodicity level and increase by PAM was also found in straw yield. High ESP greatly decreased the straw yield of plants, which was again significantly increased by PAM application. Number of grains per plant was also decreased by high sodicity, but application of PAM resulted in a gain back to the number of grains per plant in the control. At low and medium ESP levels the weight of 1000 grains remained constant and the application of PAM had no significant effect. At high ESP 1000 grain weight was significantly decreased, and significantly increased by PAM, but it was lower compared to the control. Sodicity had no effect on harvest index in the control or at low and medium ESP levels. However, at high ESP level harvest index was lower. Treatment of sodic soil with PAM resulted in a significant increase in harvest index at high ESP level. Grain and straw yield/m^2 decreased consistently with increasing sodicity levels. Grain and straw yield /m^2 were lower at high

ESP level than at low and medium levels. Treatment of sodic soil with PAM increased straw and grain yield at medium and high ESP, but not at low ESP.

6.4.6 Effects on ion concentrations in straw

The effects of medium and high ESP treatments with and without PAM on ion concentrations in the straw are shown in Table 6.5. Sodicity significantly increased Na^+ and decreased K^+/Na^+ ratio and Mn^{2+} contents in the straw at both medium and high ESP levels. High sodicity also resulted in a significant decrease in K^+ and significant increase in Fe^{2+}. Generally plants showed higher concentrations of Mg^{2+}, Zn^{2+} and Cu^{2+} in the medium ESP treatment, and lower in the high ESP treatment, although this was only significant in the case of Mg^{2+}. Sodicity had no significant effect on N concentration of straw.

Treatment of sodic soil with PAM decreased Na^+ and increased K^+/Na^+ ratio in both ESP treatments. In the medium ESP treatment, PAM had no significant effect on K^+, Ca^{2+}, Zn^{2+}, Cu^{2+}, Fe^{2+}, Mn^{2+} and Mg^{2+}. However, in the high ESP treatment PAM resulted in a significant increase in K^+, Ca^{2+} and Mn^{2+} and non-significant increase in Cu^{2+} and a decrease in Fe^{2+}.

6.4.7 Effects on ion concentrations in grains

The effects of medium and high sodicity treatments on ion concentration in grains are shown in Table 6.6. The data show that in the medium ESP treatment, grains had higher concentrations of almost all ions compared to the control treatment grains. Although, it was not statistically significant in all cases, high ESP increased the concentrations of some ions (Na^+, K^+, Ca^{2+}, Mn^{2+} and Mg^{2+}) and decreased the concentrations of other ions (K^+/Na^+ ratio, Zn^{2+}, Fe^{2+} and Cu^{2+}).

The addition of PAM in the medium ESP treatment resulted in lower concentrations of almost all ions including K^+/Na^+ ratio compared to the medium ESP without PAM treatment. However in the high ESP treatment, the addition of PAM resulted in lower values of Na^+, but higher values of K^+/Na^+ ratio and other ions.

Table 6.5. Effect of different ESP levels and polyacrylamide on the ion concentration in the straw dry matter of Kharchia- 65, grown in sodic soil

	Exchangeable sodium percentage at sowing				
Sodicity level	Control	Medium		High	
Ion content	2	29	28$^+$ PAM	44	46$^+$ PAM
Na$^+$(mg g^{-1}DM)	0.02	0.47	0.36	0.79	0.55
K$^+$(mg g^{-1}DM)	6.8	8.2	8.2	4.5	6.6
K$^+$/Na$^+$	283.2	18.4	23.2	5.1	12.3
Ca^{2+}(mg g^{-1}DM)	32.3	7.8	7.8	3.6	5.3
Mg^{2+}(ppm)	141.6	188.3	171.9	61.2	96.1
Zn^{2+} (ppm)	60.5	86.1	81.2	53.7	90.5
Cu^{2+} (ppm)	7.4	8.5	7.7	6.2	9.1
Fe^{2+} (ppm)	119.9	118.6	121.5	172.6	155.7
Mn^{2+}(ppm)	300.0	182.5	153.1	71.7	170.5
N %	1.96	1.93	1.73	-	-

	S. E. D^1	L. S. D^1	S. E. D^2	L. S. D^2
Na$^+$	0.069	0.148* * *	0.070	0.150* * *
K$^+$	0.62	1.32* *	0.63	1.35* *
K$^+$/Na$^+$	6.60	14.23* * *	6.83	14.65* * *
Ca^{2+}	14.63	N. S	15.06	N. S
Mg^{2+}	16.23	34.85* * *	16.73	35.88* * *
Zn^{2+}	16.23	N. S	16.71	N. S
Cu^{2+}	0.88	N. S	0.91	N. S
Fe^{2+}	16.24	34.85*	16.73	35.88*
Mn^{2+}	24.56	52.69* * *	25.29	54.24* * *
N	0.230	N. S	-	-
Analyses excluding control treatment values				
Na$^+$	0.078	0.172* *	0.091	0.200 * *
K$^+$/Na$^+$	2.760	6.070* * *	3.196	7.03* * *

L. S. D^1= comparison between treatments excluding high ESP.
L. S. D^2 = comparison of high ESP with all other treatments.

Table 6.6. Effect of different ESP levels and polyacrylamide on the ion concentrations in the grains of Kharchia-65, grown in sodic soils

	Exchangeable sodium percentage at sowing				
Sodicity level	Control	Medium		High	
Ion content	2	29	28+ PAM	44	46+ PAM
Na^+(mg g^{-1}DM)	0.008	0.012	0.010	0.037	0.017
K^+(mg g^{-1}DM)	2.1	2.8	1.9	3.9	4.4
K^+/Na^+	253.2	225.0	181.9	107.8	253.3
Ca^{2+}(mg g^{-1}DM)	1.7	1.9	1.6	1.8	2.4
Mg^{2+}(ppm)	133.5	180.2	176.1	179.9	233.5
Zn^{2+} (ppm)	94.8	140.1	108.3	90.4	146.9
Cu^{2+} (ppm)	7.1	8.4	6.3	4.6	7.2
Fe^{2+} (ppm)	111.9	100.8	91.4	77.1	108.5
Mn^{2+}(ppm)	84.8	111.1	99.5	117.7	186.6
N %	3.57	3.77	3.63	2.96	3.32

	S. E. D^1	L. S. D^1	S. E. D^2	L. S. D^2	significance level
Na^+	0.0020	0.0042	0.0020	0.0043	* * *
K^+	0.64	1.37	0.66	1.42	* *
K^+/Na^+	55.59	—	57.24	—	N. S
Ca^{2+}	0.310	—	0.32	—	N. S
Mg^{2+}	25.39	54.47	25.27	54.20	*
Zn^{2+}	20.67	—	21.28	—	N. S
Cu^{2+}	1.50	—	1.55	—	N. S
Fe^{2+}	19.96	—	20.55	—	N. S
Mn^{2+}	20.17	43.16	20.77	44.55	* *
N	0.095	0.206	0.116	0.25	* * *
Analyses excluding control treatment values					
Na^+	0.002	0.005	0.0021	0.0050	* * *
K^+/Na^+	55.61	—	57.25	—	N. S

S. E. D^1. and L. S. D^1.= comparison between treatments excluding high ESP.
S. E. D^2. and L. S. D^2. = comparison of high ESP with all other treatments.

6.4.8 Effects on total nutrient uptake by plants at maturity

The effects of medium and high ESP treatments with and without PAM on total nutrient uptake are shown in Table 6.7. The results show that both medium and high ESP treatments significantly increased Na^+ and significantly decreased the amounts of almost all other ions in mature plants at harvest compared to the control soil treatment. The effect of PAM was to decrease Na^+ and increase almost all other cations in both ESP treatments.

Table 6.7. Effect of different ESP levels and polyacrylamide on total ion contents in mature wheat plants at harvest

	Exchangeable Sodium Percentage before sowing				
Sodicity level	Control	Medium		High	
Ion content	2	29	28 + PAM	44	46 + PAM
	Toxic ion content/plant (mg)				
Na^+	0.02	0.21	0.19	0.29	0.22
	Macro and secondary nutrient contents/plant (mg)				
K^+	6.08	4.95	5.26	2.71	4.48
N	28.0	19.0	19.0	—	—
Ca^{2+}	8.2	4.4	4.9	1.8	3.6
Mg^{2+}(µg/plant)	181.0	165.0	190.0	76.0	136.0
	Micronutrient contents/plant (µg)				
Zn^{2+}	100	103	105	50	95
Cu^{2+}	10	8	8	5	6
Fe^{2+}	152	104	115	87	106
Mn^{2+}	265	130	136	61	144

	Equal replications		Unequal replications		significance
	S. E. D[1]	L. S. D[1]	S. E. D[2]	L. S. D[2]	level
Na^+	0.037	0.079	0.038	0.083	* * *
K^+	0.75	1.61	0.77	1.66	*
N	1.5	3.5	—	—	* * *
Ca^{2+}	0.392	0.841	0.404	0.868	* * *
Mg^{2+}	28.34	60.80	29.18	62.59	*
Zn^{2+}	12.86	27.59	13.24	28.41	* *
Cu^{2+}	1.11	2.37	1.14	2.45	*
Fe^{2+}	18.09	38.81	20.89	44.82	*
Mn^{2+}	23.21	49.79	23.90	51.27	* * *

S. E. D[1]. and L. S. D[1].= comparison between treatments excluding high ESP.
S. E. D[2]. and L. S. D[2]. = comparison of high ESP with all other treatments.

6.5 Discussion

The effects of different ESP levels in presence and absence of PAM on some important parameters of Kharchia-65 are summarised in Table 6.8.

6.5.1 Effect of $NaHCO_3$ and PAM on soil properties

The results of soil analysis are summarised in Table 6.1. It is noticeable from the EC_e values (Table 6.1) recorded at the start and end of the study, that initially the salinity was not a factor likely to influence plant performance. Although, after harvest EC_e was slightly higher, especially in the high sodicity treatment, the differences in EC_e were relatively small compared to the differences in SAR and ESP.

The values of pH, SAR and ESP in the medium and high sodicity treatments showed that the soils in these treatments were sodic in nature, compared to the control and low sodicity treatments. The increases in SAR and ESP can be attributed to the adsorption of soluble Na^+ on the exchange complex. The rise in pH of the soil in the medium and high treatments was probably the outcome of increased HCO_3^- ions in soil solution and decreased activity of Ca^{2+} . The lower values of pH, ESP and SAR in the low treatment were due to the lower concentration of $NaHCO_3$ salt added. In the low and medium sodicity treatments the SAR, ESP and pH values declined between sowing and harvest. In the high sodicity treatment SAR and ESP values did not show a marked decline, but pH did. This might be due to the application of irrigation water, which might have caused leaching, or the lower pH may be the result of excretion of some organic acids by roots in to the soil. It must also be considered that the values before sowing are based on a single sample, but after harvest the values are means of 8 replicates.

Treatment of soil with PAM stabilised the soil aggregates, hence there was a large increase in WSA % compared to the without PAM treatments. PAM also decreased soil pH, SAR and ESP in the medium and high sodicity treatments. The greater change or improvement caused by PAM in the sodic soil treatments is possibly due to the application of irrigation water (Lunt *et al.,* 1964) and more efficient drainage due to the increased WSA%. In the sodic soil treatment with PAM, WSA% was greater than in the control, suggesting that PAM not only preserved the existing aggregates but it also formed new aggregates as well.

6.5.2 Effects of sodicity on plants

The results of this study clearly show that especially in the high ESP treatment sodicity had large adverse effects on the survival, growth and development of plants (Table 6.2 and Table 6.8). Although low and medium sodicity treatments had relatively small effects on survival, number of leaves and tillers, the decrease in height was quite marked in both low and medium sodicity treatments. This indicates that different plant processes differ in their sensitivity to sodicity. The large adverse effect of high sodicity on growth and development of plants was undoubtedly because of the effect of the excessive amount of exchangeable Na^+ on both soil properties and on plants as well. These results are in agreement with Chhipa and Lal (1991), who reported that plant height and tiller number decreased with increasing ESP.

Although Kharchia-65 is regarded as a salt-resistant wheat variety (Sharma, 1991), increasing sodicity decreased grain yield and almost all yield components. In the low and medium ESP treatments sodicity decreased grain yield by 14 and 25 % respectively (Table 6.4 and Table 6.8), but the decrease was more marked (80 %) in the high sodicity treatment. At high sodicity the decrease in grain yield per plant and plant survival resulted in a 82 % decrease in grain yield/m^2.

The decrease in grain yield was due to decrease in number of grains per plant and 1000 grain weight (Table 6.4). Similar types of results have also been observed by other workers (Sharma, 1991; Gill *et al.*, 1992). In studies of the effects of sodicity on crop yield several workers have published values for the threshold level of ESP at which yield starts to decrease, and the ESP which is sufficient to cause a 50 % decrease in yield. Grain yield was decreased at the lowest sodicity level and hence in this study the threshold ESP was < 15. The value of ESP at which grain yield was decreased by 50 % was between ESP 28 and ESP 44. Sharma (1991) reported that the threshold ESP and ESP level that decreased yield of this variety by 50 % are 17.8 and 45 respectively. This suggests that Kharchia-65 was more sensitive to sodicity in this experiment than in that of Sharma (1991). Difference could also be due to different climatic conditions, growing environment etc. Generally due to the fact that the plants produced fewer tillers, and they had fewer ears, the grain yield in this experiment was lower. Gill *et al.* (1992) reported that the decrease in grain yield can also be due to the larger effect of sodicity on tillering and flowering stages of wheat.

Table 6.8. Summary table on the effects of different sodicity levels with and without PAM on survival % of plants, shoot height, grain and straw yield per plant and ion uptake. (+ and - indicate per cent increase or decrease over control respectively)

Parameter	Control	Low ESP		Medium ESP		High ESP	
Survival %	- PAM	-PAM	+ PAM	-PAM	+PAM	- PAM	+ PAM
Survival %	80.4	- 6.7	- 6.7	0.0	+ 4.3	- 71.1	- 15.5
Height (cm)	78.0	- 23.3	- 16.3	- 33.2	- 22.4	- 72.4	- 43.2
Grain wt mg/plant	549.2	- 14.4	- 13.5	- 25.3	- 13.6	- 80.0	- 25.0
Straw wt mg/plant	739.7	- 18.0	- 8.3	- 35.0	- 27.8	- 81.5	- 30.2
Ion concentration (mol m^{-3}) in flag leaf sap							
Na$^+$	2.7	+140.0	+170.0	+1930.0	+ 141.0	+ 427.0	+ 252.0
K$^+$	177.6	+ 25.8	+ 23.8	+ 27.1	+ 26.3	- 19.4	+ 12.8
K$^+$/Na$^+$ ratio	66.9	- 10.2	- 22.7	- 93.1	- 90.4	- 98.1	- 95.7

In this study sodicity also decreased straw yield both per plant and per m^2. The decrease in straw yield per plant was 18, 35 and 81 % in low, medium and high ESP treatments respectively. Chhipa and Lal (1991) have also reported similar trends of decreasing grain and straw yield of wheat with increasing soil sodicity. Although comparison of mean grain and straw yields for high ESP suggests a harvest index of 50%, the low value is because some plants produced no grains and hence the H.I was zero.

As shown in Tables 6.3, 6.5, 6.6, 6.7 and 6.8, sodicity had large effects on ion concentrations in flag leaf sap, grain and straw at maturity and on total nutrient uptake at harvest. However grain yield consistently decreased as sodicity increased, trends in ion concentrations with exception of Na^+ were less consistent. There is abundant evidence in the literature to show that high Na^+ concentrations in leaves and stems are associated with decreased grain yield. Gorham *et al.* (1997) tested the effects of a range of ESP levels on wheat. They concluded that at an ESP of 25, high leaf Na^+ (100 to 130 mol m^{-3}) was associated with low grain yield. Increase in leaf Na^+ and decrease in leaf K^+ have been associated with decreased growth and lower yield of wheat (Chhipa and Lal, 1995). The concentration of Na^+ consistently increased in grain, straw and flag leaf sap. But Mg^{2+}, K^+, Zn^{2+} and Cu^{2+} at medium sodicity were higher than the control and at high ESP were lower than the control. Although in the high ESP treatment K^+ was lower in flag leaf sap, and in straw at maturity, at low and medium ESP it was increased. Various factors have been shown to influence uptake of K^+ in sodic soils, and hence may be responsible for these observed effects. The increase in K^+ at low and medium ESP levels might be due to the enhancement in K^+ uptake caused by Na^+ ions (Moustafa *et al.*, 1966). In the high ESP treatment, the replacement of K^+ by Na^+ might have resulted in lower K^+ uptake. Lower uptake of K^+ was also possibly due to low of K^+ in the presence of high pH and ESP in the high ESP treatment. The concentration of Fe^{2+} was increased by high sodicity only in straw, but not in grains. Increasing sodicity also resulted in a marked decrease in Ca^{2+} in leaf sap and in straw at both medium and high ESP levels. Marked decreases in Ca^{2+} contents, even greater than in K^+ under sodic conditions have also been reported by other workers (Lunt *et al.*, 1964; Chhipa and Lal, 1991). This was possibly due to the lower ratio of Ca^{2+} to other cations, especially Na^+, in the soil solution, or the precipitation of Ca^{2+} which can influence the availability and uptake of Ca^{2+} ions by plants (Tisdale *et al.*, 1985).

Although effects on ion concentrations were variable, total uptake of Na^+ increased and total uptake of almost all other ions decreased generally at both, especially at high ESP level.

Although, there was a marked decrease in micronutrient uptake in the plants grown under sodic soil conditions, the resultant concentrations were not low (Epstein, 1972; Tisdale *et al.*, 1985) enough to account for the decreased growth and yield of plants that occurred in sodic conditions (Appendix 2). None of the typical micronutrient deficiency symptoms were observed in this study (Schering, 1990). For example, a concentration of Cu^{2+} below 4 ppm is considered as deficient for wheat (Caldwell, 1971). But in these results Cu^{2+} concentration in both grains and straw was above 4 ppm. Hence the low yields of plants in sodic soil are not due to micronutrient deficiency.

6.5.3 Effects of PAM

Treatment of sodic soil with PAM in this study improved the survival, growth and development of plants. Although sodicity decreased survival % in the low ESP treatment, PAM did not increase survival at low sodicity. However, at high sodicity, where the greatest decreases in height and survival % were observed, PAM had a large effect. This suggests that the effect of PAM increases with increasing sodicity. Similar effects were also noted in earlier experiments (Chapter 5). Bernstein and Pearson (1956) also found that at low ESP polymers had an inhibitory influence and at high ESP polymers had a stimulatory effect on growth of plants. However in that report it is not clearly mentioned why polymers showed a negative effect on plants at low ESP.

Treatment of sodic soil with PAM, particularly in the high ESP treatment, also gave a marked increase in grain and straw yield and all yield components (Table 6.4) compared to the high ESP treatment without PAM. In the presence of PAM, sodicity decreased grain yield per plant by 13, 14, and 25 % in low, medium and high ESP treatments respectively, compared to 14, 25, and 80 % respectively in the absence of PAM. The higher yield of grains in the medium and high ESP treatments with PAM was due to more plants surviving with ears, and more and heavier grains.

The treatments of sodic soil with PAM showed a lower decrease in straw dry weight per plant compared to the decrease shown by the same treatments without PAM. Higher yield of wheat and other crops in sodic soils treated with synthetic polymers have also been reported by Pearson and Bernstein (1958).

In the presence of PAM concentration of Na^+ decreased. Concentrations of K^+ and almost all other ions increased in both flag leaf sap as well as in mature plants at harvest. This suggests that the application of PAM was not only effective in ion uptake at the flag leaf stage but it was also effective for ion accumulation in straw and grains at maturity.

6.6 Conclusions

- At low sodicity PAM increased % WSA but grain yield per plant was unaffected.
- At medium and high sodicity PAM increased % WSA, sodium uptake decreased and yield increased.
- Grain yield at medium ESP + PAM was almost equal to the grain yield of low ESP treatment and grain yield at high ESP + PAM was more or less equal to the grain yield of medium ESP treatment.
- These results suggest that by using PAM it is possible to increase the threshold value of ESP at which yield is decreased by 50 %. This is due to a stabilisation of aggregates. It can also be concluded from this study that, although, Kharchia-65 is a salt-tolerant variety, poor soil structure still decreases its yield more than toxic ions. The relative contributions made by increased concentrations of toxic ions and poor soil structure to the decreased yields of plants in sodic soils are discussed in Chapter 11.

CHAPTER 7

Effect of high sodicity and PAM on survival, growth, ion uptake and yield of two wheat varieties, transplanted into sodic soils

CHAPTER 7

Effect of high sodicity and PAM on survival, growth, ion uptake and yield of two wheat varieties, transplanted into sodic soils

7.1 Introduction

There were two main purposes of this experiment, first to try to separate out the physical and chemical effects of high ESP by improving the structure of sodic soils with polymer (PAM). As it is already mentioned in Chapters 5 and 6, some workers have attempted to evaluate the tolerance of several crops to exchangeable sodium under greenhouse conditions. One of the objectives of these studies has been to separate the adverse effects of exchangeable sodium on physical properties from the possible direct toxicity effect. In many of these studies, either exchange resins or soil conditioners were used to maintain soil structure under sodic conditions.

The second purpose of this experiment was to investigate the performance of wheat seedlings transplanted into sodic soil (with poor and stable soil structure) as well as in the control soil. It has been reported by many workers (e.g. Mustafa *et al.,* 1966) and shown by some experiments (Experiment 2) conducted for this study, that growth in sodic soils remains satisfactory up to two weeks and then the seedlings begin to wilt. This is explained by the fact that in the first stages of growth the seedlings utilise nutrients stored in the seed. When they grow and become in need of more nutrients from such soils, they wilt and later die.

In this study an attempt was made to sow wheat directly into soil of high sodicity. This resulted in plants failing to grow after two or three weeks. Some plants were transplanted to fill the gaps of dead seedlings and these transplanted seedlings did survive to some extent at the high ESP level. That survival led to a series of experiments based on transplanting as a method of sowing, to avoid the sensitive stages of germination and early seedling establishment. These experiments are reported in this Chapter and Chapters 8 and 9.

This experiment investigated the effects of transplanting on the survival, growth, ion uptake and yield of wheat in sodic soil. Ion uptake was measured in the flag leaf, because of its importance as a source of carbohydrate for grain filling (Thorne, 1965).

Several workers have shown that sodicity has large effects on the availability and uptake of nutrients by plants (Section 2.2.4.2). Hence, to determine the effects of sodicity and PAM on uptake of macro and micronutrients, grain and straw samples were used at harvest.

7.2 Objectives

The experiment had the following objectives:

(1). To separate out the physical and chemical effects of high sodicity on wheat by using PAM to maintain the structure of a sodic soil;

(2). To determine the survival, ion uptake, growth and yield response of 12 day old seedlings transplanted into sodic soil with high ESP;

(3). To determine any varietal differences in response to high sodicity.

7.3 Materials and Methods

7.3.1 Soil preparation

The soil used in this experiment was collected from the same cultivated field as described in Chapter 6. The experiment tested 3 soil treatments (control, sodic and sodic soil with PAM). To achieve the required sodicity level, 160 kg soil was sprayed with 1M $NaHCO_3$. Another lot of 160 kg soil was sprayed with both 1M $NaHCO_3$ and 0.2 kg/100 kg soil PAM solution. The methods for spraying PAM and preparing sodic soil are described in Chapter 3 (Section 3.1).

7.3.2 Growth conditions

This experiment was also conducted in the same glasshouse as described in Chapter 6, during summer 1997. The temperature of the glasshouse was not controlled and no supplementary lighting was used. Minimum and maximum glasshouse temperatures are shown in Appendix 1.

7.3.3 Raising, transplanting and growth of seedlings

Initially in this study, seeds of Kharchia-65 and Q-19 varieties were sown directly into the soil. Although most of the seedlings emerged, plants failed to grow and develop further beyond 2 weeks. Hence, the seedlings were removed from the study and another method of sowing (transplanting) was used to grow the plants again in the same soil-filled pots.

Seeds of both wheat varieties (Kharchia-65 and Q-19) were germinated in plug trays containing compost placed in a glasshouse on capillary matting. Twelve day old seedlings were transplanted on May 20, 1997 in the late afternoon to reduce the temperature shock. There were eight replications of each soil treatment per variety. Plants were grown in pots (21x21cm surface and 21 cm deep) with drainage holes in the base, each containing the same weight of soil. Pots were arranged in a randomised complete block design on a wooden bench placed in the glasshouse. Sixteen plants of each variety were transplanted into each pot with 4 cm row to row and plant to plant distance. To ensure adequate nutrient supply, Phostrogen (@ 0.5g/l of soil) was applied three times; at the time of transplanting, 15 days after transplanting (DAT) and 30 DAT. Irrigation water was added to each pot whenever needed.

7.3.4 Plant sampling

On June 16, 1997 (27 DAT) at fully expanded flag leaf stage, six plants per treatment from each replicate of both cultivars were harvested to record the number of fully expanded leaves on the main stem, number of tillers per plant, flag leaf area (cm^2) and to obtain flag leaf sap. Flag leaves were separated from all harvested plants. Six flag leaves of each treatment per pot were combined, placed in one Eppendorf tube and stored in a freezer at - 10 ^{0}C.

7.3.5 Sap extraction and analysis

For ion analysis, the sap of frozen flag leaves was extracted following the procedure described in Chapter 3 (Section 3.2).

7.3.6 Final harvest

At maturity on August 3, 1997, the remaining plants from each pot were harvested and their height (from stem base to tip of ear), and number of tillers per plant were recorded. The mature (yellow) ears were separated and total number of spikelets per ear were counted. Threshing was done by hand, grain dry weight and number of grains were recorded. To record the straw dry weight, the remaining mass of plants was oven dried at 82 ^{0}C for 48 hours.

7.3.6.1 Preparation of grain and straw samples for chemical analysis

Dry grain and straw samples from four replicates of each treatment were prepared for the analysis of N (only in straw), and other ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, Zn^{2+} (grains only), Cu^{2+}, Mn^{2+} and Fe^{2+}) by following the methods given in Chapter 3 (Section 3.2).

7.3.6.2 Calculations

Survival % was calculated as:

$$\frac{\text{Actual no. of plants that survived with ears at maturity}}{\text{Expected total no. of mature plants at harvest (10)}} \times 100$$

7.3.7 Soil sampling and analysis

The soil used in this experiment was sampled from the pots before transplanting and after harvesting of the crop. Before transplanting one composite sample was collected from each soil treatment, but after harvesting sampling was done from each pot. The same soil properties as described in Chapter 6 were also recorded in this experiment, following the methods shown in Chapter 3 (Section 3.2).

7.3.8 Statistical analysis

The results were analysed statistically by analysis of variance (Anova), using Minitab and Genstat statistical packages. The values of the standard error of the difference between means (S. E. D.) and least significant difference (L. S. D.) were calculated using the formulae described in Chapter 4 (Section 4.3.7). As there were large differences in the values of Na^+ and K^+/Na^+ ratio between sodic and the control soil treatments, a separate analysis was performed on these data by excluding the control data. The values for Zn^{2+} content in straw were contaminated with an unexpected external Zn^{2+} source, hence the data for Zn^{2+} concentration in straw are not presented here.

7.4 Results

7.4.1 Soils

The properties of the soil before sowing and after harvesting are shown in Table 7.1. The results showed that the control soil, either before sowing or after harvest had low EC_e, SAR and ESP values. The pH of the control soil was also considered normal for UK agricultural soils. In other treatments (before sowing), where 1M $NaHCO_3$ salt was sprayed, soils showed marked increases in SAR, ESP and pH.

Table 7.1. pH, electrical conductivity (EC_e), sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), % water stable aggregates (%WSA), and texture of the soil used before sowing and after harvest

Before sowing
(values are based on single sample)

Treatment	$NaHCO_3$ added	pH (H_2O)	EC_e (dSm^{-1})	SAR	ESP
Control	No salt	6.5	1.6	1.0	0.03
Sodic	1M	9.2	3.0	73.4	52.10
Sodic + PAM	1M	8.8	3.5	62.1	47.80

Textural Class
UK classification = Clay loam soil (Hydrometer and Sedigraph methods)
USDA classification = Loam soil

After harvest
(values of chemical soil properties are the means of 16 replicates per treatment)

Treatment	$NaHCO_3$ added	pH	EC_e (dSm^{-1})	SAR	ESP	WSA%
Control	No salt	6.0	1.5	1.3	1.3	48
Sodic	1M	7.5	7.6	77.1	50.9	26
Sodic + PAM	1M	7.2	7.5	42.5	37.6	87
S. E. D.		0.06	0.50	7.30	2.61	_
L. S. D.		0.12* * *	1.01* * *	14.60* * *	5.24* * *	_

Although the sodic soil showed an increase in EC_e, it was not very high compared to the control soil. Generally, before sowing the addition of PAM into sodic soil brought a slight change in chemical properties. PAM slightly decreased pH, SAR and ESP, but slightly increased EC_e.

Most of the chemical properties changed during the course of study. In the control soil treatment there was a decrease in pH, but the values of other chemical properties were only slightly different from those before sowing. In the sodic soil there was a larger decrease in pH and increase in EC_e, but SAR and ESP did not show a big change compared to the before sowing values. In the sodic + PAM soil there were large decreases in pH, SAR and ESP and large increase in EC_e compared to the before sowing values in the same soil treatment. pH, SAR and ESP of soil with PAM were significantly lower than without PAM. The soil with PAM showed no significant difference from the soil without PAM in EC_e measured at harvest.

Sodicity resulted in a large decrease in WSA %, but PAM increased the WSA %. The WSA % in the sodic soil with PAM was greater than in the control soil.

7.4.2 Effects on survival %, growth and development of plants

Sodicity significantly decreased survival %, shoot height, number of fully expanded leaves on the main stem, flag leaf area and number of infertile tillers of transplanted seedlings (Table 7.2). PAM significantly increased the survival %, shoot height and number of leaves per plant. Over all soil treatments plants of Kharchia-65 were taller, than those of Q-19, but the mean values for number of leaves, flag leaf area and number of infertile tillers were significantly higher in Q-19 than in Kharchia-65. The interaction of sodicity x variety was only significant in shoot height and flag leaf area. Sodicity significantly decreased the height of both varieties, but the plants of Kharchia-65 were much taller in all soil treatments than those of Q-19. PAM significantly increased the shoot height in both varieties, but plants were still significantly shorter than control plants. The decrease in flag leaf area under sodic condition was greater in Q-19 than in Kharchia-65, as compared to the control plants.

Table 7.2. Effect of soil sodicity and PAM on the growth and development of two wheat varieties

Parameter	Soil treatment	Varieties		Means
		Kharchia-65	Q-19	
Survival % of plants with ears at maturity				
	Control	97.5	97.5	97.5
	Sodic	76.3	82.5	79.4
	Sodic +PAM	96.3	97.5	96.9
	Means	90.0	92.5	
Height (cm) at maturity				
	Control	69.5	44.9	57.2
	Sodic	37.7	24.6	31.1
	Sodic +PAM	56.5	35.2	45.8
	Means	54.6	34.9	
No. of fully expanded leaves on the main stem/plant (27 DAT)				
	Control	5.8	6.0	5.9
	Sodic	5.3	5.7	5.5
	Sodic +PAM	5.8	6.0	5.9
	Means	5.6	5.9	
Flag leaf area (cm^2)				
	Control	4.4	8.9	6.7
	Sodic	2.4	2.5	2.4
	Sodic +PAM	3.3	3.7	3.5
	Means	3.4	5.1	
No. of fertile tillers/plant (at maturity				
	Control	6.3	8.5	7.4
	Sodic	0.0	0.0	0.0
	Sodic +PAM	0.0	1.6	0.8
	Means	2.1	3.4	

	Sodicity		Variety		Sodicity*variety	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
Survival %	5.05	10.15* *	4.12	N. S	7.14	N. S
Height	2.26	4.54* * *	1.80	3.70* * *	3.20	6.40*
No. leaves/p	0.16	0.32*	0.13	0.26*	0.23	N. S
Leaf area (cm^2)	0.65	1.30* * *	0.53	1.07* *	0.92	1.85* *
No. tillers/p	0.67	1.36* * *	0.55	1.11*	0.96	N. S

7.4.3 Effects on ion concentration and K^+/Na^+ ratio in the flag leaf sap

Table 7.3 shows the effects of sodicity and PAM on ion concentration and K^+/Na^+ ratio in the flag leaf sap of both varieties. Plants grown in the sodic soil treatment had significantly higher Na^+ and significantly lower K^+, K^+/Na^+ ratio, Ca^{2+} and Mg^{2+} than in the control soil treatment.

Table 7.3. Effect of high ESP with and without PAM on ion concentration in the flag leaf sap of two varieties

Ion (mol m^{-3})	Soil treatment	Variety		Means
		Kharchia-65	Q-19	
Na^+				
	Control	2.3	2.4	2.3
	Sodic	230.0	235.5	232.8
	Sodic +PAM	131.3	130.5	130.9
	Means	121.2	122.8	
K^+				
	Control	192.8	280.8	236.8
	Sodic	162.0	212.8	187.4
	Sodic +PAM	180.4	231.3	205.8
	Means	178.4	241.6	
K^+/Na^+				
	Control	101.5	138.5	120.0
	Sodic	0.8	0.9	0.9
	Sodic +PAM	1.5	1.8	1.7
	Means	34.6	47.1	
Ca^{2+}				
	Control	20.8	22.8	21.8
	Sodic	7.7	11.4	9.4
	Sodic +PAM	13.1	15.6	14.3
	Means	13.8	16.5	
Mg^{2+}				
	Control	26.0	20.5	23.3
	Sodic	16.0	21.4	18.7
	Sodic +PAM	19.3	23.3	21.2
	Means	20.4	21.7	

	Sodicity		Variety		Sodicity*variety	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
Na^+	14.94	30.02* * *	12.20	N. S	21.10	N. S
K^+	10.70	21.48* * *	8.73	17.50* * *	42.76	N. S
K^+/Na^+	10.77	21.60* *	8.79	N. S	15.24	N. S
Ca^{2+}	1.27	2.56* * *	1.04	2.08*	1.80	N. S
Mg^{2+}	1.25	2.51* * *	1.01	N. S	1.76	3.55* * *
Analysis excluding control soil treatment						
Na^+	18.29	37.45* * *	18.29	N. S	25.87	N. S
K^+/Na^+	0.12	0.25* * *	0.10	N. S	0.17	N. S

Treatment of sodic soil with PAM significantly decreased Na^+, and significantly increased K^+/Na^+ ratio, Ca^{2+} and Mg^{2+}, compared to the without PAM treatment. Although PAM increased the concentration of K^+, it was not statistically significant. Over all soil treatments, Q-19 had significantly higher concentration of K^+ and Ca^{2+} than Kharchia-65, but there were no significant differences between varieties for other ions. The interaction of sodicity x variety was non significant in all cases, except Mg^{2+}, which was significantly lower in Kharchia-65 under sodic conditions than Q-19.

7.4.4 Effects on ion concentrations in wheat grains

The results indicated (Table 7.4a) that in the sodic soil treatment the concentrations of Na^+ and K^+ were significantly increased. The concentrations of Ca^{2+} and Mg^{2+} were also increased but the differences were statistically non significant. K^+/Na^+ ratio was significantly decreased by sodicity. Treatment of soil with PAM decreased Na^+ and hence increased K^+/Na^+ ratio, compared to the sodic soil without PAM treatment.

Over all soil treatments, Q-19 showed higher values of almost all cations including K^+/Na^+ ratio than Kharchia-65. There was no significant interaction between sodicity x variety, except for K^+/Na^+ ratio. Ca^{2+} content was higher in Q-19 than Kharchia-65 in all soil treatments. In the sodic soil treatment K^+/Na^+ ratio was lower in Q-19 and higher in Kharchia-65, compared to other soil treatments, where K^+/Na^+ ratio was higher in Q-19 than Kharchia-65.

The data for micronutrients (Table 7.4b) revealed that sodicity significantly decreased Zn^{2+} and Mn^{2+} concentrations in grains. However, there was also a slight decrease in Cu^{2+} and an increase in Fe^{2+} concentrations, but these effects were not significant. Similarly, as in the case of macronutrients (Table 7.4a), Q-19 had higher mean values for all micronutrients except Mn^{2+} in grains. However, the interaction was not significant in all cases. PAM significantly increased Zn^{2+} and Mn^{2+} in both varieties, but effects on Fe^{2+} and Cu^{2+} were non significant.

Table 7.4a. Effect of soil sodicity and PAM on the concentrations (mg/g) of Na^+, macro and secondary nutrients in wheat grains

Ion (mg/g)	Soil treatment	Variety		Means
		Kharchia-65	Q-19	
Na^+				
	Control	0.005	0.005	0.005
	Sodic	0.150	0.530	0.339
	Sodic +PAM	0.098	0.076	0.087
	Means	0.083	0.205	
K^+				
	Control	1.56	2.52	2.03
	Sodic	2.90	3.20	3.06
	Sodic +PAM	3.11	3.23	3.17
	Means	2.52	2.99	
K^+/Na^+				
	Control	274.6	478.1	376.3
	Sodic	22.6	16.9	19.8
	Sodic +PAM	35.3	47.6	41.5
	Means	110.9	180.9	
Ca^{2+}				
	Control	1.30	1.50	1.40
	Sodic	1.43	2.50	1.97
	Sodic +PAM	1.60	2.30	1.92
	Means	1.42	2.10	
Mg^{2+}				
	Control	0.17	0.21	0.19
	Sodic	0.26	0.22	0.24
	Sodic +PAM	0.22	0.29	0.26
	Means	0.22	0.24	

	Sodicity		Variety		Sodicity*variety	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
Na^+	0.051	0.106*	0.104	N. S	0.182	N. S
K^+	0.29	0.61*	0.24	N. S	0.41	N. S
K^+/Na^+	17.87	37.36* * *	14.52	30.50* * *	25.15	52.84* * *
Ca^{2+}	0.33	N. S	0.27	0.57*	0.47	N. S
Mg^{2+}	0.03	N. S	0.28	N. S	0.046	N. S

Table 7.4b. Effect of soil sodicity and PAM on the micronutrient concentrations (ppm) in wheat grains

		Variety		
Nutrient (ppm)	Soil treatment	Kharchia-65	Q-19	Means
Zn^{2+}				
	Control	167.6	163.4	165.5
	Sodic	100.7	84.3	92.5
	Sodic +PAM	137.0	174.8	155.8
	Means	135.0	140.8	
Fe^{2+}				
	Control	71.8	79.9	75.9
	Sodic	69.0	142.0	105.5
	Sodic +PAM	84.5	126.8	105.6
	Means	75.1	116.2	
Mn^{2+}				
	Control	158.6	131.9	145.3
	Sodic	125.3	87.0	106.0
	Sodic +PAM	141.0	141.3	141.0
	Means	141.5	120.0	
Cu^{2+}				
	Control	4.9	6.3	5.6
	Sodic	3.3	5.7	4.5
	Sodic +PAM	5.0	5.0	4.8
	Means	5.3	5.6	

	Sodicity		Variety		Sodicity*variety	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
Zn^{2+}	21.43	45.03* *	17.50	N. S	30.30	N. S
Fe^{2+}	19.51	N. S	15.92	33.46*	27.58	N. S
Mn^{2+}	12.98	27.30*	10.60	N. S	18.36	N. S
Cu^{2+}	0.77	N. S	0.63	N. S	1.01	N. S

7.4.5 Effects on ion concentrations in wheat straw

Na^+ and N concentrations in straw were significantly higher, while K^+, Ca^{2+}, Mg^{2+} and K^+/Na^+ ratio were significantly lower in the plants grown in the sodic soil treatment than in the control soil treatment (Table 7.5a). The treatment of soil with PAM had no significant effect on Na^+ and Mg^{2+}concentrations, but resulted in slight increases in K^+/Na^+ ratio and K^+, Ca^{2+} and N concentrations in straw compared to the sodic soil treatment.

In the control soil treatment K^+/Na^+ ratio was higher in Kharchia-65 than Q-19, but not in other soil treatments. The differences between varieties x sodicity for other ions were largely non significant.

Table 7.5a. Effect of soil sodicity and PAM on the N % and concentrations (mg/g) of Na^+, macro and secondary nutrients in straw (stem + leaves) at maturity

		Variety		
Nutrient (mg/g)	Soil treatment	Kharchia-65	Q-19	Means
Na^+				
	Control	0.02	0.09	0.05
	Sodic	0.93	0.83	0.88
	Sodic +PAM	0.91	0.89	0.90
	Means	0.62	0.60	
K^+				
	Control	17.7	17.2	17.5
	Sodic	4.9	5.3	5.1
	Sodic +PAM	4.8	6.0	5.4
	Means	8.9	9.5	
K^+/Na^+				
	Control	1215.0	676.0	945.4
	Sodic	5.0	7.0	6.0
	Sodic +PAM	5.0	7.0	6.2
	Means	408.6	229.8	
Ca^{2+}				
	Control	17.4	14.2	15.8
	Sodic	5.6	5.7	5.7
	Sodic +PAM	6.5	5.7	6.1
	Means	9.8	8.5	
Mg^{2+}				
	Control	0.23	0.18	0.21
	Sodic	0.13	0.16	0.14
	Sodic +PAM	0.15	0.13	0.14
	Means	0.18	0.16	
N (%)				
	Control	1.2	0.9	1.1
	Sodic	2.6	2.6	2.6
	Sodic +PAM	2.8	2.5	2.7
	Means	2.2	2.0	

	Sodicity		Variety		Sodicity*variety	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
Na^+	0.063	0.134* *	0.052	N. S	0.089	N. S
K^+	0.76	1.62* *	0.62	N. S	1.07	N. S
K^+/Na^+	96.63	210.60* * *	78.90	171.70*	136.66	297.79*
Ca^{2+}	0.84	1.80 * *	0.69	N. S	1.19	N. S
Mg^{2+}	0.009	0.019* *	0.008	0.017*	0.013	N. S
N	0.15	0.31* * *	0.12	N. S	0.20	N. S
Analysis excluding control						
K^+/Na^+ ratio	0.84	N. S	0.84	N. S	1.19	N. S

Table 7.5b. Effect of soil sodicity and PAM on the micronutrient concentrations (ppm) in wheat straw (stem + leaves)

		Variety		
Nutrient (ppm)	Soil treatment	Kharchia-65	Q-19	Means
Fe^{2+}	Control	168.3	364.0	266.1
	Sodic	232.0	336.5	284.3
	Sodic +PAM	231.0	209.3	220.1
Means		210.4	303.0	
Mn^{2+}				
	Control	552.3	356.8	454.5
	Sodic	49.0	63.5	56.3
	Sodic +PAM	55.5	59.3	57.4
Means		218.9	159.8	
Cu^{2+}				
	Control	13.3	13.5	13.4
	Sodic	6.5	6.3	6.4
	Sodic +PAM	9.0	8.3	8.6
Means		9.6	9.4	

	Sodicity		Variety		Sodicity*variety	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
Fe^{2+}	37.00	N. S	30.20	64.36* *	52.30	111.45*
Mn^{2+}	30.90	65.85* *	25.20	53.70*	43.70	93.12* *
Cu^{2+}	1.05	2.24* *	0.86	N. S	1.49	N. S

In the case of micronutrients (Table 7.5b) sodicity significantly decreased Mn^{2+} and Cu^{2+}, but the effect on Fe^{2+} was non significant. PAM decreased Fe^{2+} and slightly increased Mn^{2+} and Cu^{2+}, but the effects were non significant. Over all soil treatments Q-19 had significantly higher Fe^{2+} and significantly lower Mn^{2+} than Kharchia-65. The interaction of varieties x sodicity was significant in Fe^{2+} and Mn^{2+} but not in Cu^{2+}. Q-19 had significantly higher Fe^{2+} and lower Mn^{2+} than Kharchia-65 in the control soil treatment. Concentration of Fe^{2+} was also significantly higher in Q-19 than Kharchia-65 in the sodic soil treatment. PAM significantly decreased Fe in Q-19 but not in Kharchia-65.

7.4.6 Effects on grain and straw yield and yield components

Tables 7.6a and b show the effects of sodicity and PAM on grain and straw yield and yield components of both varieties tested. At maturity all plants consisted of one mainstem only, with no tillers. Although, sodicity significantly decreased grain and straw yield, effects of sodicity on grain yield were greater than on straw yield, so that H. I. was

Table 7.6a. Effect of soil sodicity and PAM on the yield components of two wheat varieties

		Variety		
Parameter	Soil treatment	Kharchia-65	Q-19	Means
No.ears/plant				
	Control	1.0	1.0	1.0
	Sodic	1.0	1.0	1.0
	Sodic +PAM	1.0	1.0	1.0
	Means	1.0	1.0	
No. spikelets /ear				
	Control	10.9	14.3	12.6
	Sodic	9.2	11.6	10.4
	Sodic +PAM	11.0	12.7	11.9
	Means	10.4	12.9	
No. grains/plant				
	Control	9.6	8.5	9.1
	Sodic	2.3	1.3	1.8
	Sodic +PAM	4.2	1.3	2.7
	Means	5.4	3.7	
1000 grain wt (g)				
	Control	37.0	41.6	39.3
	Sodic	16.1	17.2	16.6
	Sodic +PAM	16.8	26.1	21.4
	Means	23.3	28.3	
Harvest index (%)				
	Control	31.4	27.6	29.5
	Sodic	18.5	11.6	15.1
	Sodic +PAM	14.1	8.9	11.5
	Means	21.4	16.1	

	Sodicity		Variety		Sodicity*variety	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
No. ears/plant	-	-	-	-	-	-
No.spikelets/ear	0.34	0.69* * *	0.28	0.56* * *	0.48	0.97*
No. grains/plant	0.78	1.57* * *	0.64	1.28*	1.10	N. S
1000 grain wt (g)	1.88	3.79* * *	1.54	3.10* *	2.67	N. S
H. I. (%)	2.52	5.08* * *	2.06	4.15*	3.57	N. S

Table 7.6b Effect of sodicity and PAM on the straw and grain yield

Yield	Soil treatment	Variety Kharchia-65	Q-19	Means
Grain wt/plant (mg)				
	Control	356.7	367.5	362.1
	Sodic	38.4	25.9	32.2
	Sodic +PAM	69.9	32.9	51.4
	Means	155.0	142.1	
Straw wt/plant (mg)				
	Control	791.0	880.0	835.8
	Sodic	186.0	176.3	181.0
	Sodic +PAM	399.7	328.2	364.0
	Means	458.8	461.7	
Grain yield/m^2 (g)				
	Control	218.1	225.3	221.7
	Sodic	19.7	14.1	16.9
	Sodic +PAM	42.4	20.2	31.3
	Means	93.4	86.5	
Straw yield/ m^2 (g)				
	Control	483.0	534.5	508.8
	Sodic	98.5	96.3	97.2
	Sodic +PAM	242.0	200.0	221.0
	Means	274.3	276.9	

	Sodicity S. E. D.	L. S. D.	Variety S. E. D.	L. S. D.	Sodicity*variety S. E. D.	L. S. D.
Grain wt/p	34.00	68.40* * *	27.79	N. S	48.15	N. S
Straw yield/p	55.20	110.9* * *	45.05	N. S	78.00	N. S
Grain yield/m^2	21.51	43.20* * *	17.60	N. S	30.40	N. S
Straw yield/m^2	33.50	67.30* * *	27.44	N. S	47.43	N. S

significantly lower in the sodic soil treatment. Sodicity significantly decreased number of grains per plant, 1000 grain weight, and number of spikelets per ear. Treatment of sodic soil with PAM increased grain and straw yield and almost all yield components. The increase was significant for 1000 grain weight and straw yield per plant but not for grain yield /plant and per m^2. Sodicity and PAM had no effects on number of ears per plant at maturity. As sodicity and PAM affected survival, straw and grain weight per plant, they had larger effects on grain and straw yield per m^2. Decreases in grain and straw weight per plant were greater in Q-19 than Kharchia-65, the increases in grain and straw yield per plant in response to PAM were greater in Kharchia-65 than Q-19. However the sodicity x variety interaction was non significant.

7.5 Discussion

7.5.1 Soil (Table 7.1)

The original soil used in this study was clay loam with low organic matter, N (Table 5.1), EC_e, SAR and ESP. A marked change occurred in SAR, ESP and pH of the original soil following addition of $NaHCO_3$ salt. Originally the soil was non saline and non sodic, but treatment of soil with $NaHCO_3$ salt resulted in a sodic soil with high sodicity (Qureshi and Lennard, 1998). As the original soil was already low in organic matter, and clay loam, it became a sodic soil with properties typical of sodic soils in Pakistan (Rajpar, 1996). He found similar types of properties in salt-affected soils of district Hyderabad Sindh. As described in Chapters 5 and 6 the main reason for the change in chemical properties is likely to be the dissociation of $NaHCO_3$ salt. The increase in soil pH may to some extent be an effect of HCO_3^- ions, and the precipitation of Ca^{2+} and to some extent Mg^{2+}. This also agrees with the reports of several workers (Qureshi and Lennard, 1998; Singh and Totawat, 1994).

The values of pH, ESP and SAR were slightly lower in the presence of PAM than in the absence of PAM. This also agrees with the soil results of Chapters 5 and 6. The lower values of SAR and ESP in the presence of PAM are possibly due to less precipitation and slightly greater solubility of Ca^{2+} and Mg^{2+}. Thus adding PAM into sodic soil may be one way of decreasing pH, ESP and SAR.

An addition of $NaHCO_3$ salt also resulted in a drastic decrease in WSA %, which shows that the soil in the sodic treatment had poor physical condition. The deterioration of soil structure was most likely associated with the dispersion of colloidal particles saturated with exchangeable Na^+. A marked increase in soil aggregation occurred by adding PAM at the equivalent sodicity level. That increase in soil aggregation in the presence of the soil conditioner was probably the result of the various functions of PAM as reported by several workers. For example, Ben-Hur and Keren (1997) reported that an anionic polymer most probably has a relatively long grappling distance, that facilitates the formation of inter-particle bridges. As in other experiments (Chapters 5 and 6), PAM resulted in increased production of larger sized (2 to 5 mm and over 5 mm) water stable soil aggregates in this study. Similar types of effects were also recorded by Martin and Jones (1954).

There were large differences in chemical soil properties measured at sowing and after harvest. The large decrease in SAR and ESP in sodic soil with PAM treatment was possibly due to leaching. The marked increase in EC_e in both the sodic and sodic plus PAM treatment was possibly due to the solubility of adsorbed Na^+, by using irrigation water.

7.5.2 Effects of soil sodicity and PAM on plants

Effects of sodic soil treatments with and without PAM on some important plant characters are shown in summary Table 7.7.

7.5.2.1 Effects of sodicity on plants

The results (Table 7.7) obtained from this study showed that although sodicity was quite high (Qureshi and Lennard, 1998), the survival of transplanted seedlings in sodic soil treatments was good compared to that of seedlings grown from seed. This indicates that using rooted seedlings transplanted into sodic soils, avoids their initial sensitive stage. McFarland *et al.* (1990) also found that rooted stem cuttings of some salt-bush species survived better than direct sown seeds when re-vegetating salt-affected soils.

It is also apparent from the results (Table 7.7) of this study that, although almost 80 % of the transplanted seedlings survived, sodicity markedly decreased their shoot height, number of leaves, leaf area and number of tillers. This effect of sodic soil treatment on the growth and development of plants was associated with the high SAR, ESP and pH. These effects are well documented in the Literature Review (Section 2.2.5.2) and have also been observed in other experiments reported in this study.

Sodicity significantly decreased grain and straw yield. The significant decrease in grain yield per plant was due to lighter and fewer grains. The decrease in grain yield per m^2 was due to lower survival of plants with lower per plant yield. The lower straw weight per plant was most probably the result of fewer tillers and shorter plants, which, combined with lower survival, resulted in lower straw weight per m^2.

Although, it was generally lower in almost all soil treatments, harvest index was significantly lower in the sodic soil treatment than the control. The significantly lower harvest index was clearly due to lower grain weight in all soil treatments. This indicates

Table 7.7. Summary table showing the % changes (increase or decrease (-) over the control). The values for Na^+ are given as times greater (*) than the control.

Parameter	% Change			% Change			
	Control (actual value)	*Sodic*	*Sodic+PAM*	*Sodic*		*Sodic +PAM*	
				KHR-65	**Q-19**	**KHR-65**	**Q-19**
Survival %	97.5	-18.6	- 0.6	-21.7	-15.4	-1.2	0.0
Height (cm)	57.2	-45.6	-19.9	-45.8	-45.2	-23.0	-21.6
Flag leaf area (cm^2)	6.7	-64.2	-47.8	-45.5	-71.9	-25.0	-58.0
No. spikelets/ear	12.6	-17.5	- 5.5	-13.2	-18.9	0.9	-11.2
1000 grain wt (g)	39.3	-58.0	-45.5	-56.5	-58.7	-54.6	-37.3
Grain wt (mg/p)	362.1	-91.1	85.8	-89.2	-92.9	-80.4	-91.0
Straw wt (mg/p)	835.8	-78.3	-56.5	-76.4	-80.0	-49.5	-62.7
Ion concentration (mol m^{-3}) and K^+/Na^+ ratio in the flag leaf sap							
Na^+(times)	2.3	*101.2	*56.9	*100.0	*57.1	*98.1	*54.4
K^+	236.8	- 20.9	- 13.1	- 16.0	- 6.4	- 24.2	- 17.6
K^+/Na^+ ratio	120.0	- 99.2	- 98.6	- 99.2	- 98.5	- 99.4	- 98.7
Ca^{2+}	21.8	- 56.9	- 34.4	- 62.9	- 37.0	- 50.0	- 31.6
Mg^{2+}	23.3	- 19.7	- 9.0	- 38.5	- 25.8	- 4.4	- 13.7

the effect of sodicity on grain yield was greater than on straw yield. The values of H. I. in the control plants were lower than those usually reported in the literature (around 50 %) as this treatment had a large number of infertile secondary tillers which were mixed in while recording the shoot dry weight.

As noted in other experiments, in this study PAM increased the survival %, shoot height, number of fully expanded leaves on the main stem and flag leaf area. This might be because plants in the sodic soil treatment with PAM showed lower Na^+ and greater K^+ and other nutrient cations in their leaf sap. The significant effect of PAM on flag leaf area was most likely due to the lower concentration of Na^+, which may have facilitated the increase in cell division and decrease in leaf the. In agreement with Azmi and Alam (1990) who reported that increased Na^+ in wheat decreased cell division and increased leaf thickness. Another reason could be the lower ESP value in the presence of PAM than in its absence.

7.5.2.2 Effects on ion uptake

Due to high ESP soil sodicity significantly increased Na^+ in flag leaf sap (Table 7.7), straw (Table 7.5a) and grains (Table 7.4a). There was a decrease in K^+ in flag leaf sap and straw but not in grains under sodic conditions. This suggests that in leaves and stem due to the higher concentration of Na^+ there was less accumulation of K^+, but in grains where Na^+ was not in very high concentration this did not occur. Due to higher Na^+ and lower K^+, K^+/Na^+ ratio was lower in leaf sap, straw and grains. Sodicity also decreased Ca^{2+} and to some extent Mg^{2+} in leaf sap and straw, but not in grains. The lower concentrations of Ca^{2+} and Mg^{2+} were probably due to the lower solubility of these cations in soil solution, due to their precipitation. Lower Ca^{2+}, K^+ and Mg^{2+} uptake by plants at high ESP has also been reported by other workers (Section 2.2.3.2).

The results (Table 7.4b and Table 5b) of this study also indicated that although soil sodicity influenced the uptake of micronutrients, their concentrations did not reach levels considered to be toxic or deficient (Epstein, 1972). Furthermore the plants in this study did not show micronutrient toxicity or deficiency symptoms in any of the soil treatments tested. These effects on micronutrients concentrations are possibly associated with presence of high Na^+ and HCO^-_3 ions and the nutrient imbalance caused by high soil pH (Singh and Totawat, 1994). This suggests that low yields in the sodic treatment were due to high concentrations of toxic ions and poor soil structure etc., but not due to effects on micronutrients. Decrease in micronutrient contents in wheat under sodic condition has also been reported by Padole (1991).

In the sodic soil treatment with PAM, there was a considerable decrease in Na^+ and increase in K^+/Na^+ ratio and in almost all other cations. The decrease in Na^+ and increase in other ions may also be attributable to the lower value of SAR and ESP in the soil before sowing, and markedly lower values after harvest, which might have been reflected in lower absorption of Na^+ and higher uptake of other nutrients.

7.5.2.3 Varietal effects

The experiment tested two varieties, Kharchia-65 and Q-19. When these varieties were tested in solution culture (Chapter 4), they showed differential responses to salinity (Kharchia-65 tolerant and Q-19 sensitive). However, the results (Table 7.7) of this study clearly indicate that, although the % decreases over the control in some parameters, especially in flag leaf area and number of spikelets, were greater in Q-19 than Kharchia-65, the decreases in survival %, shoot height, straw and grain yield were more or less similar in both the varieties. The lack of significant differences between the varieties in most of the parameters was associated with almost equal concentrations of Na^+ in flag leaves. However the varieties did show slight differences in other parameters.

The two varieties showed similar responses to PAM for shoot height and survival. However for flag leaf area, number of spikelets, grain and straw yield the response to PAM was smaller in Q-19 than in Kharchia-65 (Table 7.7). Contrarily, for tiller number and 1000 grain weight the response was greater in Q-19 than Kharchia-65. However, as for most of these parameters, including yield, the variety x sodicity interaction was non significant, the results provided no evidence of varietal differences in response to sodicity and PAM.

7.6 Conclusions

This experiment, supports the idea that under sodic soil conditions transplanted seedlings can survive up to maturity, However they still absorb more Na^+ and less K, hence they show poor performance and give lower yield than plants in non-sodic soil. The effect of PAM indicates that even at high ESP at least part of the decrease in plant survival, grain and straw yield in sodic soil is due to the adverse soil physical conditions.

Although several workers have suggested that wheat is tolerant to sodicity at later growth stages, the results of this study are not in the support of this idea.

CHAPTER 8

Effect of soil salinity, sodicity and PAM on the growth, ion uptake and yield of 16 day old transplanted seedlings of Kharchia-65 & Q-19

CHAPTER 8

Effect of soil salinity, sodicity and PAM, on the growth, ion uptake and yield of 16 days old transplanted seedlings of Kharchia-65 and Q-19

8.1 Introduction

In experiment 2 salinity and sodicity resulted in marked decreases in seedling emergence and growth, indicating that wheat was sensitive to these stresses at this growth stage. This experiment was conducted to determine the effects of salinity and sodicity after establishment on the growth and yield of wheat, and to determine if it is possible to obtain satisfactory growth and yield by avoiding stress at the germination and emergence stage by using transplanted seedlings. Although it may be difficult to transplant wheat seedlings under field conditions, this method may improve the performance of wheat under highly saline or sodic soil conditions.

This experiment compared the growth, ion uptake and yield of two wheat varieties (Kharchia-65 and Q-19) sown as transplanted seedlings into saline and sodic soil with and without PAM. Two further experiments (8 and 9) were conducted in two different soils to investigate the feasibility of this technique and these are reported in Chapter 9.

8.2 Objectives

The experiment had the following specific objectives:

(1). To study the effects of high soil salinity and sodicity on wheat;

(2). To study the effects of soil salinity, and sodicity with and without PAM on:
  (a) ion content in the shoot dry matter at the flag leaf stage,
  (b) growth,
  (c) yield of wheat;

(3). To find out if there are differences in response to high salinity and sodicity between salt resistant (Kharchia-65) and susceptible (Q-19) wheat varieties.

(4). To determine if it is possible to obtain satisfactory growth of wheat in saline and sodic soils by using transplanted seedlings.

8.3 Materials and methods

8.3.1 Soil preparation

After recording seedling emergence percentage in Experiment 2 (Chapter 5), the pots containing the prepared soil of the control, saline, sodic and sodic plus PAM treatments were re-used in this experiment.

8.3.2 Growth conditions

This experiment was conducted in a glasshouse at the Henfaes Agricultural Research Station, Bangor, during summer 1997. Temperature was not controlled and no supplementary lighting was used. Maximum and minimum temperatures are shown in Appendix 1.

8.3.3 Raising and transplanting of seedlings

In this study 16 day old seedlings were obtained from the same nursery stock raised in the glasshouse for Experiment 6 (refer to Chapter 7, Section 7.3.3). Seedlings of two wheat varieties viz. Kharchia-65 and Q-19 were transplanted from the compost trays into the soil filled pots on May 23, 1997. At the time of transplanting the seedlings had 5 leaves emerged and were 20 cm high. There was one pot of each treatment. There were ten plants of each variety in each pot arranged in two adjacent lines at 8 cm row to row and plant to plant spacing. The application of fertiliser and irrigation were as in Experiment 6 (Section 7.3.3).

8.3.4 Plant sampling, preparation and analyses of ions

When the flag leaf was fully expanded, on June 18 1997 (22 DAT), five plants were harvested at random from each treatment and the roots removed. The height, number of tillers per plant and number of fully expanded leaves on the main stem of the harvested plants were recorded. The leaves and stems were oven dried, at 70 ^{0}C for 40 hr, ground using a pestle and mortar and then ashed overnight in a muffle furnace at 450 ^{0}C. The ash was then digested in acid (5M, HCl) for further ion analyses using an atomic absorption spectrophotomter. The methods of sample preparation and ion (Na^+, K^+, Ca^{2+} and Mg^{2+}) analyses are given in Chapter 3 (Section 3.2). Ion concentrations were determined on a whole plant (above ground) basis rather than using sap extraction as the plants in sodic soil treatments were small and it was not possible to obtain sufficient sap for analysis.

8.3.5 Final harvest

At maturity, on July 29 1997, the remaining plants of both varieties from the saline, sodic and sodic with PAM treatment were harvested by cutting at soil level. Plants of the control treatment were harvested 15 days later because of delayed maturity. The harvested plants were oven dried at 82 ^{0}C for 48 hr. The ears were separated from straw and threshed by hand. Grains were cleaned and weighed and the number of grains per plant and straw dry weight per plant were determined.

8.3.6 Soil analyses

Before sowing and after harvesting of plants, soil samples were collected and analysed for chemical (Na^+, K^+, Ca^{2+} and Mg^{2+}, pH, EC_e) and physical (texture and water stable aggregate %) properties. As this experiment was conducted in the same soil after harvesting the seedlings of Experiment 2 (Chapter 5), the details for sampling, preparation and analyses of soil before sowing are given in Chapter 5 (Section 5.3.2.1) and Chapter 3 (Sections 3.1 and 3.2).

8.3.7 Statistical analyses

The results of this experiment were analysed in two ways. A combined analysis of variance was performed on the data for both varieties and all soil treatments. Two additional separate analyses were performed by dividing the data into two sets. The first data set consisted of the results of the sodic, sodic + PAM and control soil treatments and the second data set consisted of the results obtained from the saline and control soil treatments. All data sets were subjected to analysis of variance (ANOVA) using Minitab statistical package version 10.51. The output of both (combined and separate) analyses was compared. For almost all the parameters the significance levels of the various factors (variety, soil treatments and variety x soil treatments) were similar in these analyses.

There were minor differences in the ANOVAS for Mg^{2+}, 1000 grain weight and harvest index, but these were considered to be relatively un-important. The analyses of the most important parameters (Na^+, K^+, K^+/Na^+ and grain weight/plant) gave identical results in terms of which effects were significant and non significant. Hence, the results of the combined ANOVA are presented here.

As there were very large differences in the values of Na^+ and K^+/Na^+ ratio between salt affected (sodic, sodic plus PAM and saline) treatments and the control, separate analyses were performed on these data in which the data for the control were excluded. Both varieties had no grains at all in the sodic soil treatment. Hence, this treatment was excluded and the ANOVA was performed on the number of grains per plant and all grain dependent parameters using the results of control, saline, and sodic plus PAM treatments only.

The standard error of the difference between means (S. E. D.) and least significant difference (L. S. D.) were calculated as in Chapter 5 (Section 5.3.2.6). Prior to analysis of variance, all data were tested for homogeneity of variance using Bartlletts test, using the appropriate Macro routine in Minitab statistical package.

8.4 Results

8.4.1 Soil characteristics

The detailed results of soil analyses before sowing for pH, EC_e, SAR, ESP, texture and water stable aggregates % are described in Chapter 5 (Table 5.1).

The results of the soil analysis after harvesting of plants (Table 8.1) show that the EC_e of the saline soil treatment was very high, compared to the control, sodic and sodic plus polymer soil treatments. The pH of the control and saline soil was within the range normally considered to be optimum for plant growth. The sodic soil had a high pH, greater than that of the control and saline soil, but slightly below the accepted threshold ($pH > 8.5$) normally used to define a sodic soil. The high sodicity treatments, in the presence and in absence of PAM, showed higher SAR and ESP than the control and saline soil treatments.

Table 8.1 pH, EC_e (dSm^{-1}), SAR and ESP and water stable aggregates (% WSA) before sowing and after harvest

	Soil treatments			
Properties	Control	Saline	Sodic	Sodic + PAM
		Before sowing		
pH	6.5	5.0	8.8	8.5
EC_e	3.6	18.6	8.3	6.7
SAR	1.3	10.6	64.1	58.2
ESP	<0.1	12.7	48.6	46.2
WSA %	71.0	not measured	38.0	73.0

Texture Clay loam (UK classification)

After harvest

	Soil treatments			
Properties	Control	Saline	Sodic	Sodic + PAM
pH	6.3	6.4	7.7	8.0
EC_e	2.0	24.7	6.8	6.8
SAR	1.0	13.6	32.2	37.0
ESP	<0.1	15.0	32.0	35.2

8.4.2 Survival %

Plants grown from the transplanted seedlings in each treatment showed 100 % survival up to maturity and all plants had ears.

8.4.3. Effects on growth and development

The effects of soil salinity and sodicity with and without PAM on the height, number of main stem leaves and number of tillers per plant are shown in Table 8.2. The plants in the salt-affected soil treatments were significantly shorter than the control plants. The effect of sodicity was greater than salinity. Plants in sodic soil with PAM were slightly taller than the plants in soil without PAM. The varieties exhibited a significant difference in plant height. Generally, Kharchia-65 plants were significantly taller than Q-19 in all soil treatments. Plants in the salt-affected soil treatments showed a small but non-significant increase in the number of fully expanded leaves on the main stem. Although in the control soil treatment Q-19 had fewer leaves than Kharchia-65, the differences between varieties and the interaction of soil treatments with varieties were not significant. In the control soil treatment both varieties produced three tillers, and in the saline soil treatment only Kharchia-65 had a single tiller. There was no tiller formation in both varieties in all sodic soil treatments.

Table 8.2. Effect of soil salinity, sodicity and PAM on the height, number of leaves and number of tillers per plant. Values are the means of 5 plants of each variety per treatment harvested at flag leaf stage (22 DAT)

		Variety		
Parameter	Soil treatment	Kharchia-65	Q-19	Means
Height (cm)				
	Control	68	41	54.6
	Saline	47	27	37.2
	Sodic	26	16	21.3
	Sodic +PAM	30	20	25.0
	Means	42.9	26.1	
No. of fully expanded main stem leaves/plant				
	Control	6	5	5.7
	Saline	7	7	6.8
	Sodic	7	7	6.8
	Sodic +PAM	7	7	6.7
	Means	6.5	6.5	
No. of tillers /plant				
	Control	3	3	2.9
	Saline	1	0	0.5
	Sodic	0	0	0.0
	Sodic +PAM	0	0	0.0

	Soil treatment		Variety		Soil trt * Variety	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
Height	2.6	5.3* * *	8.3	16.9* * *	3.7	7.5* *
No. of leaves	0.2	N. S	0.3	0.5* *	0.4	N. S
No. of tillers	0.2	N. S	0.3	0.6* * *	0.4	N. S

8.4.4 Effects on ion concentration

The concentrations of Na$^+$ was significantly increased, while that of K$^+$, and K$^+$/Na$^+$ ratio were significantly decreased in the salt affected soil treatments (Table 8.3). The salt treatments had no effect on Mg^{2+} concentration of shoot dry matter. There were differences between the plants of the saline and sodic soil treatments. The concentration of Na$^+$ was significantly higher and that of K$^+$ and K$^+$/Na$^+$ ratio were significantly lower

Table 8.3. Effect of soil sodicity, salinity and PAM on the concentration (mg g^{-1}) of ions in the dry matter (stem + leaves) of two wheat varieties

Ion	Soil treatments	Variety		Means
		Kharchia-65	Q-19	
Na^+				
	Control	0.9	1.2	1.07
	Saline	5.0	1.9	3.45
	Sodic	12.1	10.3	11.19
	Sodic +PAM	4.2	8.9	7.08
	Means	5.55	5.85	
K^+				
	Control	40.1	54.2	47.15
	Saline	23.6	32.2	27.92
	Sodic	13.4	19.2	16.32
	Sodic +PAM	14.3	21.5	17.91
	Means	22.9	31.6	
Ca^{2+}				
	Control	0.52	0.48	0.503
	Saline	3.35	2.67	3.011
	Sodic	0.07	0.09	0.078
	Sodic +PAM	0.11	0.11	0.109
	Means	1.011	0.839	
Mg^{2+}				
	Control	0.02	0.03	0.024
	Saline	0.03	0.02	0.026
	Sodic	0.02	0.04	0.028
	Sodic +PAM	0.01	0.04	0.023
	Means	0.020	0.033	
K^+/Na^+				
	Control	44.0	55.7	49.82
	Saline	6.3	21.5	13.87
	Sodic	1.1	2.0	1.56
	Sodic +PAM	3.9	2.8	3.36
	Means	16.33	20.17	

	Soil treatment		Variety		Soil trt * variety	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
Na^+	1.01	2.05* * *	0.71	N. S	1.43	2.89* *
K^+	3.09	6.29* * *	2.19	4.45* * *	4.38	N. S
Ca^{2+}	0.213	0.434* * *	0.151	N. S	0.301	N. S
Mg^{2+}	0.798	N. S	0.565	N. S	1.130	2.29*
K^+/Na^+	5.75	11.69* * *	4.07	N. S	8.14	N. S
Analyses excluding control soil treatment						
Na^+	1.16	2.39* * *	0.95	N. S	1.64	3.38* *
K^+/Na^+	2.52	5.19* * *	2.05	4.24*	3.56	7.34* * *

in the plants of the sodic soil treatment than in the saline soil treatment. The concentration of Ca^{2+} was significantly higher in the plants of the saline soil treatment than the sodic and other treatments. In contrast treatment of sodic soil with PAM significantly decreased Na^+ but increased K^+, Ca^{2+} and K^+/Na^+ ratio in the plant dry matter.

There were significant differences between the varieties in the concentration of K^+, but not other ions, where Q-19 had significantly higher K^+ than Kharchia-65. The ANOVA in which the data for the control were excluded showed that Na^+ was significantly decreased by PAM in Kharchia-65 but not in Q-19. The increase in K^+/Na^+ ratio by PAM was also greater in Kharchia-65 than Q-19. However, in the saline soil treatment Kharchia-65 had significantly higher Na^+ and lower K^+/Na^+ ratio than Q-19.

8.4.5 Effects on grain yield and yield components

In each treatment all plants survived to produce ears. Salt treatments significantly decreased grain yield and components (Table 8.4a). The effects of variety, and the variety x salt treatment interaction were not significant. Straw dry weight per plant and harvest index were also significantly decreased by saline and sodic soil treatments (Table 8.4b). The effects of sodicity on yield and all yield components were greater than the effects of salinity. Although in the sodic soil treatment plants had ears, there were no grains in them at all. Therefore the values for grain weight and harvest index were zero in this soil treatment for both varieties. Kharchia-65 had higher straw dry weight than Q19 in all soil treatments, although the difference between varieties was significant in the control only. Contrarily, in the saline soil treatment, grain yield and other yield components were slightly higher in Q-19 than Kharchia-65. Plants of Q19 in the sodic + PAM treatment showed higher straw weight than plants in the sodic treatment, but they produced no grain. Plants of Kharchia-65 produced a few small grains in the sodic + PAM treatment and also had higher straw weight than plants in the sodic treatment.

Table 8.4 (a). Effect of soil salinity, sodicity and PAM on the number of ears, number of grains, grain yield (mg) per plant and 1000 grain weight (g). Values are the means of 5 plants of each variety per treatment

Parameter	Soil treatment	Variety Kharchia-65	 Q-19	Means
No. of ears /plant				
	Control	3.4	3.2	3.30
	Saline	1.0	1.0	1.00
	Sodic	1.0	1.0	1.00
	Sodic +PAM	1.0	1.0	1.00
	Means	1.60	1.55	
No. of grains/plant				
	Control	61	64	62.4
	Saline	5	7	6.0
	Sodic	0	0	0.0
	Sodic +PAM	3	0	1.4
	Means	17.0	17.8	
Grain yield (mg/plant)				
	Control	2691	2399	2545.1
	Saline	150	252	201.0
	Sodic	0	0	0.0
	Sodic + PAM	44	0	22.0
	Means	721.3	662.8	
1000 grain weight (g)				
	Control	45	38	41.6
	Saline	30	38	32.2
	Sodic	0	0	0.0
	Sodic + PAM	10	0	4.8
	Means	21.0	18.2	

	Soil treatment S. E. D.	 L. S. D.	Variety S. E. D.	 L. S. D.	Soil trt * Variety S. E. D.	 L. S. D.
No. of ears/p	0.16	0.32* * *	0.35	N. S	0.22	N. S
No. of grains/p	4.3	8.7* * *	3.0	N. S	6.0	N. S
Grain wt/p	155.2	309.2* * *	107.6	N. S	215.2	N. S
1000 grain wt	7.5	15.3* * *	1.7	N. S	3.4	N. S
Analyses excluding sodic soil treatment						
No. of grains/p	4.0	8.4* * *	5.0	N. S	7.0	N. S
Grain wt/p	143.5	296.1* * *	175.7	N. S	248.5	N. S
1000 grain (g)	1.8	3.8* * *	2.3	N. S	3.2	N. S

Table 8.4 (b). Effect of soil salinity, sodicity and PAM on the straw dry weight (mg/plant) and harvest index (%). Values are the means of 5 plants of each variety per treatment

		Variety		
Parameter	Soil treatment	Kharchia-65	Q-19	Means
Straw dry weight (mg/plant)				
	Control	2360	1144	1752.0
	Saline	468	342	405.0
	Sodic	208	112	160.0
	Sodic + PAM	332	176	254.0
	Means	842	443.5	
Harvest Index (%)				
	Control	53	67	60.2
	Saline	24	40	31.8
	Sodic	0	0	0.0
	Sodic + PAM	11	0	5.5
	Means	21.9	26.7	

	Soil treatment		Variety		Soil trt * Variety	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
Straw wt/p	94.4	191.1* * *	66.8	135.6	133.5	271.4* * *
H.I. (%)	3.2	6.6* * *	2.3	4.6	4.6	9.3* *
Analysis excluding sodic soil treatment						
H.I. (%)	3.1	6.3* * *	3.74	N. S.	5.3	10.9* *

8.5 Discussion

8.5.1 Soil properties

The soil used in this experiment was clay loam (UK classification) with 21 % clay and 3.8 % organic carbon. When this soil was treated with salts it showed properties typical to those of saline and sodic soils of arid and semi-arid regions. After harvesting, the saline soil showed high EC_e, but the soils of the sodic treatments with and without PAM showed low EC_e and pH but high SAR and ESP. De-Sigmond (1938) also reported that sodic soils can show pH as low as 6, but the ESP of these soils can still be very high (>15). He used the term degraded for such sodic soils. Application of PAM in the presence of high ESP increased the % WSA, which confirms that the soil treated with polymer had an improved physical condition (stable structure) compared to the untreated sodic soil.

8.5.2 Effects of soil salinity and sodicity on plants

The effects of saline and sodic (with and without PAM) soil treatments on some important parameters of transplanted plants are summarised in Table 8.4.

In experiment 2 (Chapter 5) seeds sown directly into these soils decreased germination and establishment (Table 5.1.1 and Table 5.1.2). However, in this experiment the survival percentage of transplanted plants was 100 % in all soil treatments. The increased survival of plants in salt treatments was probably due to the raising of seedlings past the initial sensitive stage in compost, and their later transfer into the salt treatments. It has been confirmed by several workers (Ratner, 1935; Pearson and Bernstein, 1958; Sharma, 1991) that wheat plants are more tolerant to sodicity and salinity at later stages than at initial (emergence and seedling) stages. Farooq *et al.* (1995) also showed that transplanted wheat seedlings can perform well in salt-affected soils.

The results obtained in this experiment showed that overall the effects of sodicity on shoot height, number of tillers (Table 8.1), grain yield, grain yield components (Table 8.3a) and straw dry weight (Table 8.3 b) were greater than the effects of salinity. Table 8.5 shows that the decreases in almost all parameters due to sodicity were greater than the decreases due to salinity.

It is clear from the Table 8.5, that salinity and sodicity resulted in marked decreases in straw dry weight per plant (77 and 91 % respectively). Salinity decreased grain yield per plant by 92 %, but in the sodic treatments plants did not produce grains. Other workers (Farooq *et al.*, 1995) have also found that salinity (EC_e 9 to 32) and sodicity (20 to 55 ESP) greatly decrease straw and grain yield of wheat. The plants in sodic treatments in this study produced straw and ears, but no grains, suggesting that sodicity had adverse effects on pollination, fertilisation and or seed setting.

The decrease in grain yield in the saline treatment was due to the absence of tillers, lighter and fewer grains, whereas the decreased grain yield in the sodic soil treatment was due to the empty ears and absence of tillers. It has also been reported by many workers (Joshi, 1976; Mass *et al.*, 1990) that decreased tillering is the main cause for low crop yield in salt-affected soils of arid and semi-arid regions.

The greater effect of sodicity than salinity on plants was associated with greater effects on ion content (Table 8.3). As was expected, the effect of salinity on plants was

Table 8.5. Summary table showing the effect of salinity and sodicity with and without PAM on some important characters of two wheat varieties (+ and - indicate per cent increase or decrease over control respectively). The values for Na$^+$ are given as times greater or lower than control

Parameter	Effects of soil treatments			Varietal effects					
	Saline	Sodic	Sodic+PAM	Saline		Sodic		Sodic +PAM	
				Khar-65	Q-19	Khar-65	Q-19	Khar-65	Q-19
Growth									
Height	- 32	- 61	- 54	- 31	- 34	- 62	- 61	- 56	-51
No. tillers	- 83	- 100	- 100	- 67	- 100	- 100	- 100	- 100	-100
Ion concentrations in plant dry matter									
Na$^+$	3	11	7	6	2	13	9	5	7
K$^+$	- 40	- 65	- 62	- 41	- 55	- 67	- 65	- 64	- 60
K$^+$/Na$^+$	- 72	- 97	- 93	- 86	- 61	- 98	- 96	- 91	-95
Ca^{2+}	499	- 84	- 78	538	456	- 87	- 81	- 79	-77
Mg^{2+}	8	17	- 4	50	- 33	0	33	- 50	- 33
Yield and yield components									
Grain wt/plant	- 92	- 100	- 99	- 94	- 90	- 100	- 100	- 98	-100
No. grains/plant	- 90	- 100	- 98	- 92	89	- 100	- 100	- 95	- 100
1000 grain wt	- 23	- 100	- 89	- 33	- 0	- 100	- 100	- 78	- 100
Straw wt/plant	- 77	- 91	- 86	- 80	- 70	- 91	- 90	- 86	- 49
H.I.	- 47	- 100	- 91	- 55	- 40	- 100	- 100	- 79	- 100

to increase Na^+, Ca^{2+} and decrease K^+ and K^+/Na^+ ratio but Mg^{2+} was unaffected compared to the control plants. The increase in Na^+ and Ca^{2+} content may be attributed to the increased amount of sodium and calcium ions in the soil solution due to the addition of salts when the soils were prepared. Although in the saline treatment Mg^{2+} salt was also mixed into the soil, the plants did not show higher Mg^{2+} than control plants, possibly because of higher Ca^{2+} uptake. Sodicity resulted in a larger increase in Na^+ and a larger decrease in K^+, Ca^{2+} and K^+/Na^+ ratio than salinity. The concentration of Mg^{2+} was unaffected by salinity or sodicity. The greater increase in Na^+ content was possibly due to the higher ESP level. The greater decrease in K^+ and Ca^{2+} may be due to the antagonistic effect of Na^+ or, as it is often found (Gutschik and Kay 1995), that nutrients are retained more in the root under stress conditions than in the shoots. Similar effects of sodicity on ion content of various plants have been reported by many workers (Bains and Fireman, 1964; Lunt *et al.*, 1964). Ratner (1935) reported that wheat plants were unable to absorb Ca^{2+} from soil having an ESP of 40. In the case of Mg^{2+} some reports indicate a decrease in sodic soils while others (Moustafa, *et al.*, 1966) indicate slight or no effect of sodicity on Mg^{2+}.

8.5.3 Effects of PAM

Synthetic polymers improve the physical properties of sodic soils (Allison, 1952; Lunt *et al.*, 1964; Morsey *et al.*, 1991) and in return they improve plant performance (Allison, 1952). In this experiment anionic polyacrylamide soil conditioner (PAM) had a marked effect on the performance of wheat plants. Averaged over the 2 varieties, the treatment of sodic soil with PAM increased straw weight by 59 %. Grain weight was 22 mg/plant compared to the same sodicity treatment in the absence of PAM where there was no grain yield. These results are also comparable with the findings of Lunt *et al.* (1964) who reported that the performance of plants in sodic soil was improved by using synthetic polymer (VAMA).

Treatment of sodic soil with PAM decreased Na^+ and increased K^+ and Ca^{2+} contents in the plants. Lunt *et al.* (1964) have also reported a decrease in Na^+ and increase in K^+ and Ca^{2+} content of plants using polymers at a range of ESP (12 to 28) levels.

8.5.4 Varietal response

The experiment tested two varieties, Kharchia-65 and Q-19. In solution culture (Chapter 4) these varieties had been found to be resistant (Kharchai-65) and susceptible (Q-19) to salinity. Several other workers have also reported that Kharchia-65 is resistant to both salinity (Joshi *et al.*, 1985) as well as sodicity (Singh and Rana, 1985; Sharma, 1987, 1991). However, in this study the reverse trend was found in the saline treatment. Q-19 had both higher grain yield and a lower % decrease in grain yield over the control than Kharchia-65. The higher yield of Q-19 than Kharchia-65 was due to it having a greater number of heavier grains. In addition, straw yield was decreased by 80 % in Kharchia-65 but by only 70% in Q-19. Q-19 also had higher harvest index in both the control as well as in the saline treatment. The higher yield of Q-19 was associated with lower Na^+, and higher K^+ and K^+/Na^+ ratio than Kharchia-65. However, there are no clear reasons why the relative performance of the varieties differed in the two culture systems, It could be due to several factors, for example, the involvement of various processes in ion uptake viz, contact exchange process that can only occur in the presence of colloidal particles.

This study also provided some evidence that the varieties also differed in response to sodicity and PAM. Although both varieties had no grains, the straw yield of both varieties was decreased by 90 % under sodic conditions. An improvement in grain yield and yield components by PAM was observed only in Kharchia-65. However the effects of PAM on straw weight were greater in Q-19 than Kharchia-65. Treatment of sodic soil with PAM resulted in a larger decrease in Na^+ in Kharchia-65 than in Q-19. The effects of PAM on concentrations of other ions were similar in the two varieties. Hence there were no consistent relationships between effects of PAM on growth, yield and ion concentrations.

The results of this experiment should be treated with some caution, as there was only one replicate pot of each treatment, and the levels of each salinity and sodicity tested were very high.

8.6 Conclusions

The results obtained from this experiment suggest that seedlings transplanted into salt-affected soil can survive up to maturity, but the yield of survived plants may still be low. The improvement of aggregation in sodic soil by using anionic polyacrylamide and the transplanting of wheat seedlings into this can also result in improved performance. These results also suggest that the response of varieties observed in solution culture (Chapter 4) may not be the same in soil culture.

CHAPTER 9

Effect of soil sodicity on survival, ion uptake and yield of wheat plants grown from dry seed, pre-germinated seed and seedlings transplanted after 16 and 21 days

CHAPTER 9

Effect of soil sodicity on survival, ion uptake and yield of wheat plants grown from dry seed, pre-germinated seed and seedlings transplanted after 16 and 21 days

9.1 Introduction

The effects of salts on plants are not the same throughout the growth period, but vary with age of the plants and also depend on crop species. The effects of sodicity on some crops like cowpeas and groundnuts are small in the early stages of plant growth, but increase with advancement in the age of the crops (Singh and Abrol, 1984). However, a reverse trend was reported for Brassica crops (Singh *et al.,* 1980). Cereal crops like maize, rice and wheat are most sensitive at the early seedling stage and become increasingly tolerant as they mature (Rowell, 1994).

Head *et al.* (1950) reported that under field conditions it is possible that modification of planting practices to minimise the tendency for salt to accumulate around the seed can improve the establishment of crops that are sensitive to salt during germination. McFarland *et al.* (1990) found that transplanting of rooted seedlings and cuttings of bushes can be applied for revegetation of salt-affected soils. However, increasing population pressures and shortage of food emphasise the need to improve the yield of economically important crops rather than revegetation of salt affected soils. Countries like Pakistan have sufficient labour, but are facing a serious problem of wheat shortage due to the lower yields caused by salinity and sodicity.

The results of experiments 2 and 7 suggested that wheat is sensitive to sodicity at an early stage, but it can grow and survive satisfactorily under sodic soil conditions at later stages. This study investigated the effect of two sodic soils (loamy sand and clay loam) on ion uptake and yield of salt resistant wheat variety Kharchia-65 (Section 6.1) established by different sowing methods. Among sowing methods 2 seed stages viz., dry and pre-germinated seed, and 2 transplanting stages viz., 16 and 21 day old seedlings were tested.

9.2 Objectives

Two experiments were conducted for this study with the following objectives:

(1). To find out the stage of wheat sensitive or resistant to sodicity;

(2). To compare seed sowing and transplanting methods of sowing;

(3). To compare the survival, ion uptake and yield of wheat grown from different sowing methods at low and high sodicity levels;

(4). To study the effects of sodicity in loamy sand and clay loam soils.

9.3 Materials and methods

Both experiments were identical in all cases, apart from the soil type. The first experiment was conducted in clay loam soil and the second experiment was conducted in loamy sand soil. The experimental design was a randomised complete block with 4 replications. Each experiment tested three sodicity treatments (control, low and high) combined factorially with four sowing methods (sowing of dry and pregerminated seed and transplanting of 16 and 21 day old seedlings).

9.3.1 Soil preparation

The method of soil preparation was similar to that described in Chapter 5 (Section 5.3.2.1). To generate low and high sodicity, the soil (clay loam for experiment 8 and loamy sand for experiment 9) was treated with 0.25M and 0.75M $NaHCO_3$ salt respectively, using the method explained in the Chapter 3 (Section 3.1.1).

9.3.2 Growth conditions

Both experiments were conducted in the same walk-in growth chamber set at 18 °C day and 9 °C night temperature, 65% RH with a photoperiod of 16 hours, at Henfaes Agricultural Research Station, University of Wales, Bangor, UK, during the period December 1997 to April 1998.

9.3.3 Sowing treatments

In each experiment the plants were grown in pots (10cm x10 cm surface x 16cm deep). Each pot contained 9 plants at a spacing of 4 cm. The salt resistant variety

Kharchia-65 was used in both experiments. The seed for all sowing treatments was sown on 1 December 1997. In the case of dry seed it was sown directly into the pots. In the case of pre-germinated seed it was placed on moist filter paper in petri dishes placed in incubator set at 20 °C. After five days, when radicle was 1.5 mm and the plumule was 1.2 mm, the seedlings were sown in the soil filled pots.

Seedlings for transplanting were raised by sowing dry seed in plastic trays filled with compost. After sixteen, when the plants had approximately 10 cm shoot height and 5.5 cm root length, seedlings were transferred in to soil filled pots (treatment 3). Again at 21 days well developed seedlings (14 cm tall) with more extensive root system, were transferred in to the appropriate pots (treatment 4). The method of raising and transplanting seedlings is also explained in Chapter 7 (7.3.3).

9.3.4 Irrigation and fertiliser

The pots were watered regularly to replace losses by evapotranspiration. To ensure sufficient nutrition, Phostrogen (Chapter 4, Section 4.3.4) fertiliser was applied to each pot, using the same rate and method as explained in the Chapter 7.

9.3.5 Leaf sampling, extraction and chemical analysis of sap

When they became fully expanded, the flag leaves of two plants from all pots of each treatment were removed, placed in Eppendorf tubes and stored at -10 ^{0}C in a freezer. Leaf sap was extracted and analysed for Na^+, K^+, Ca^{2+} and Mg^{2+} as described in the Chapter 3 (Section 3.2).

9.3.6 Final harvest

At maturity all plants were harvested by cutting at soil level. Plants which had previously been sampled for chemical analysis and those without ears were not incorporated in the yield data of both experiments. Ears of the survived plants were separated from straw and were placed in separate paper bags for drying at 82 ^{0}C for 48 hr. Threshing was done by hand and the data for grain yield and yield components of both experiments were recorded. The values presented were calculated on the basis of the number of plants survived (with ears at harvest) at maturity. Survival %, grain and straw weight per m^2 were calculated using the following formulae:

$$\text{Survival \%} = \frac{\text{number of plants that survived with ears at maturity}}{\text{number of plants sown per pot}}$$

$$\text{Grain or straw weight /m}^2 = \frac{\text{Grain or straw yield per pot}}{\text{Pot area (m}^2\text{)}}$$

9.3.7 Soil analysis and calculation

Soil samples from each control, low and high sodicity treatment were analysed before sowing, and a composite (over all replications) sample from the control, low and high sodicity treatments was collected and analysed after harvest. Samples were prepared and used to analyse chemical (Na^+, K^+, Ca^{2+}, Mg^{2+}, pH and EC_e, total N % and total C %) and physical (texture) properties of soil.

9.3.8 Statistical analysis

The mean values of the plant data recorded for ion uptake, yield and yield components of both experiments were analysed by analysis of variance, using the Minitab statistical package. The standard error of the difference between means (S. E. D.) and the least significant difference (L. S. D.) were calculated, applying the same formulae as in Chapter 4 (Section 4.3.7). The data for survival % were transformed into arcsine values prior to using balanced anova. To determine the effects of sodicity and sowing method on the different soil types, the results of both experiments were combined and re-analysed using three-way (soil type x sodicity level x sowing method) analysis of variance.

9.4 Results

9.4.1 Experiment 8

Effect of soil sodicity on plants grown from dry and pregerminated seed and the seedlings transferred after 16 and 21 days in to clay loam soil

9.4.1.1 Soil characteristics

Prior to sowing and application of salt treatments, the pH value of the soil was typical to that of a well managed agricultural soils in the UK, it was non saline with low

Table 9.1. pH, electrical conductivity (EC_e), sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), total carbon %, total nitrogen % and texture of the soil before sowing and after harvesting

ESP level	Control	Low	High
Salt applied	No salt	0.25M, $NaHCO_3$	0.75M, $NaHCO_3$
		Before sowing	
EC_e (dSm^{-1})	2.0	2.7	4.0
pH (1:2.5 H_2O)	6.6	8.1	9.0
SAR	4.1	17.4	44.6
ESP	4.6	19.9	39.6

Texture
Sand total = 46.8 %
2000-----------630µm = 9.0 %
630µm--------200µm = 17.7 %
200µm---------63µm = 20.0 %
Silt ---------- ----- = 34.1 %
Clay -------------- - = 19.2 %
Class ------------ -- = Clay loam soil (UK classification)
Total carbon % 3.80
Total N% 0.28

After harvesting

ESP level	Control	Low	High
Salt applied	No salt	0.25M, $NaHCO_3$	0.75M, $NaHCO_3$
EC_e (dSm^{-1})	1.1	2.5	3.5
pH (1:2.5, H_2O)	6.8	8.2	8.9
SAR	1.8	10.0	33.0
ESP	1.4	11.9	32.5

SAR and ESP values (Table 9.1). The soil was not deficient in total carbon and total nitrogen. There was a consistent increase in the values of chemical properties (pH, EC_e, ESP and SAR) of the soil following application of $NaHCO_3$. The greatest increase in the values of pH, ESP and SAR occurred at high concentration of salt. Although the EC_e increased with increasing salt concentration, it remained lower than the value associated with a saline soil (4 dSm^{-1}).

During the course of the experiment EC_e and pH showed little change, but the values of SAR and ESP decreased.

9.4.1.2 Visual observations

At high sodicity plants grown from dry and pre-germinated seed had dark green coloured leaves and stems up to maturity. These plants showed a delay in maturity and were harvested one week later than the plants grown from transplanted seedlings. At the time of harvesting, plants at high sodicity had dry and mature heads, but their remaining parts were green.

9.4.1.3 Survival %

The effects of sodicity on survival % are shown in Table 9.2. The survival % of plants in the control was not significantly different from that at low sodicity. However, survival % of plants was significantly decreased at high ESP. The effect of time at which the seed and seedlings were introduced into the soil was also significant. High sodicity had a greater effect on dry and pre-germinated seed compared to the seedlings which were initially raised in compost and later transferred in to the soil.

Table 9.2. Effect of low and high sodicity and sowing method on survival % of Kharchia-65 under clay loam soil condition

	Sodicity			
	Control	Low	High	Means
ESP	5	20	40	
Parameter				
Survival (%)				
Dry seed	100	100	82	94.0
Pre-germinated seed	100	100	64	88.1
16 day old seedlings	100	100	100	100.0
21 day old seedlings	100	100	100	100.0
Means	100.0	100.0	86.6	
Transformed data [arcsine (%/100)]				
Dry seed	1.57	1.57	1.04	1.39
Pre-germinated seed	1.57	1.57	0.81	1.32
16 day old seedlings	1.57	1.57	1.57	1.57
21day old seedlings	1.57	1.57	1.57	1.57
Means	1.57	1.57	1.25	

Standard error of the difference between means and least significant difference for transformed data

	Sodicity		Method		Sodicity*Method	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
Survival %	0.064	0.129 * * *	0.074	0.150* *	0.128	0.261* * *

The survival % of plants grown from dry and pre-germinated seed was significantly lower than that of the control plants. However, the plants grown from transplanted seedlings showed 100 % survival in all sodicity treatments. At high sodicity sowing of pre-germinated seed resulted in lower survival than dry seed.

9.4.1.4 Ion concentrations in the flag leaf sap

The effect of increasing sodicity was to increase Na^+, and decrease K^+, Ca^{2+}, Mg^{2+} and K^+/Na^+ ratio in the flag leaf sap (Table 9.3). The effect of sowing method and the sowing method x sodicity interaction in almost all cases were not significant. There were no clear trends in Na^+ and K^+ with sowing method. Generally in all soil treatments transplanted plants had slightly but non significantly higher Ca^{2+} and significantly higher Mg^{2+} than the plants had in other sowing methods.

9.4.1.5 Yield and yield components

Low sodicity had no significant effect on yield and yield components (Table 9.4). However, the plants grown at high sodicity had significantly lower grain yield and yield components. At high sodicity plants had fewer grains/plant, lower grain weight/plant, lower 1000 grain weight and also lower grain weight/m^2, than in the control. In the case of straw yield, the plants grown at high sodicity had significantly lower straw weight /plant and per m^2 compared to the control plants. In general (over all sodicity treatments), transplanted seedlings gave significantly higher grain yield and yield components than dry and pre-germinated seed. However, sowing method had no significant effect on the number of ears per plant and 1000 grain weight. Transplanted seedlings also had significantly higher straw weight, and significantly higher harvest index (Table 9.4b). Although the sodicity x sowing method interaction was not significant, at high sodicity the grain and straw weight of transplanted seedlings was considerably greater than that of dry and pre-germinated seed. The increase in grain weight was mainly due to more grains/plant. High sodicity decreased grain yield /plant of the plants established from dry and pre-germinated seed by 74 and 92 % respectively. The corresponding decreases in grain yield per plant of the plants from 16 and 21 day old seedlings were 16 and 36 % respectively. The greater yield /plant combined with higher survival % (Table 9.2), resulted in a higher grain yield /m^2. For grain yield and yield components sowing of dry seed gave slightly higher values than sowing of pre-germinated seed and 16 day old seedlings gave slightly higher values than 21 day old seedlings although the differences were not significant. Transplanting of 16 and 21 day old seedling gave significantly higher straw weight /m^2 than other methods.

Table 9.3. Effect of low and high sodicity and sowing method on ion concentrations in the flag leaf sap of Kharchia-65, under clay loam soil condition

	Sodicity			
	Control	Low	High	Means
ESP	5	20	40	
Na^+ mol m^{-3}				
Dry seed	2	18	211	76.8
Pre-germinated seed	2	18	178	65.8
16 day old seedlings	2	30	157	63.1
21 day old seedlings	3	32	241	91.7
Means	2.2	24.2	196.5	
K^+ mol m^{-3}				
Dry seed	276	264	130	223.1
Pre-germinated seed	216	236	142	198.0
16 day old seedlings	255	250	178	227.5
21 day old seedlings	261	289	138	229.2
Means	251.9	259.5	146.9	
K^+/Na^+ ratio				
Dry seed	147.0	19.0	0.6	55.4
Pre-germinated seed	123.0	18.0	0.9	47.4
16 day old seedlings	118.0	16.0	1.6	45.1
21 day old seedlings	102.0	11.0	0.6	37.8
Means	122.4	16.0	0.9	
Ca^{2+} mol m^{-3}				
Dry seed	25	13	5	14.1
Pre-germinated seed	26	13	6	14.7
16 day old seedlings	30	17	8	18.0
21 day old seedlings	37	25	8	23.0
Means	29.1	16.6	6.6	
Mg^{2+} mol m^{-3}				
Dry seed	22	17	9	15.6
Pre-germinated seed	18	15	8	13.7
16 day old seedlings	25	19	14	19.2
21 day old seedlings	27	23	11	20.1
Means	22.9	18.1	10.5	

	Sodicity		Method		Sodicity*Method	
	S. E. D	L. S. D	S. E. D	L. S. D	S. E. D	L. S. D
Na^+	10.8	22.0* * *	12.4	N. S	21.6	N. S
K^+	17.0	35.0* * *	20.0	N. S	34	N. S
K^+/Na^+	10.8	22.0* * *	12.4	N. S	21.5	N. S
Ca^{2+}	3.1	6.3* * *	3.6	N. S	6.2	N. S
Mg^{2+}	2.0	4.0* * *	2.3	4.7*	3.9	N. S

Table 9.4(a). Effect of low and high sodicity on grain yield and grain yield components of Kharchia-65, grown under clay loam soil conditions

	Sodicity			
	Control	Low	High	Means
ESP	5	20	40	
No. of ears/plant				
Dry seed	1.6	1.6	1.3	1.50
Pre-germinated seed	2.0	1.9	1.6	1.85
16 day old seedlings	1.8	2.0	1.5	1.78
21 day old seedlings	2.1	1.9	1.7	1.90
Means	1.89	1.87	1.51	
No. grains/plant				
Dry seed	35	28	10	24.4
Pre-germinated seed	29	33	3	22.0
16 day old seedlings	35	37	28	33.5
21 day old seedlings	37	40	27	34.7
Means	34.2	34.6	17.1	
Grain wt/plant (mg)				
Dry seed	1710	1477	438	1208.5
Pre-germinated seed	1473	1790	120	1115.8
16 day old seedlings	1717	2004	1459	1726.9
21 day old seedlings	1758	2038	1147	1647.9
Means	1655.7	1827.6	791.0	
Grain yield/m^2 (g)				
Dry seed	1069	923	243	745.0
Pre-germinated seed	898	1119	37	684.6
16 day old seedlings	1073	1252	912	1079.2
21 day old seedlings	1098	1273	717	1029.8
Means	1034.8	1142.2	477.1	
1000 grain wt (g)				
Dry seed	49	52	45	48.5
Pre-germinated seed	48	53	38	46.4
16 day old seedlings	49	55	51	51.5
21 day old seedlings	47	52	42	47.0
Means	48.3	53.1	43.7	

	Sodicity		Method		Sodicity*Method	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
No. ears/p	0.211	N. S	0.244	N. S	0.422	N. S
No. grains/p	3.8	7.7* * *	4.4	8.8*	7.5	N. S
1000 grain wt	1.9	3.9* * *	2.2	N. S	3.8	N. S
Grain wt/p	188.0	381.6* * *	217.0	440.6*	375.9	N. S
Grain yield/m^2	117.1	238.0* * *	135.2	275.0*	234.3	N. S

Table 9.4 (b). Effect of low and high sodicity on straw wt/plant and /m^2 (g) and harvest index (%) of Kharchia-65, grown under clay loam soil conditions

	Sodicity			
	Control	Low	High	Means
ESP	5	20	40	
Straw wt/plant (mg)				
Dry seed	1736	1651	634	1340.3
Pre-germinated seed	1944	1988	399	1443.7
16 day old seedlings	1716	2074	1669	1819.9
21 day old seedlings	1829	1944	1455	1742.7
Means	1806.0	1914.6	1039.4	
Straw yield/m^2 (g)				
Dry seed	1085	1032	346	820.9
Pre-germinated seed	1214	1242	148	868.5
16 day old seedlings	1072	1297	1043	1137.4
21 day old seedlings	1142	1215	910	1089.1
Means	1128.7	1196.6	611.7	
Harvest Index (%)				
Dry seed	50	47	38	44.5
Pre-germinated seed	42	46	25	37.6
16 day old seedlings	50	50	47	48.6
21 day old seedlings	49	51	44	47.8
Means	47.4	48.4	38.1	

	Sodicity		Method		Sodicity*Method	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
Straw wt/p	177.0	359.4* * *	204.4	N. S	354.1	N. S
Straw yield/m^2	109.1	221.5* * *	126.0	255.8*	218.4	443.1*
H. I (%)	2.5	5.2* * *	2.9	5.9* *	5.1	N. S

9.4.2 Experiment 9

Effect of soil sodicity on plants grown from dry and pre-germinated seed and seedlings transferred after 16 and 21 days into loamy sand soil

9.4.2.1 Soil characteristics

The analysis of the original soil used in this study showed that at the beginning of the experiment, the pH of soil was typical of that a well managed agricultural soil in the UK and it was non saline with low values of SAR and ESP (Table 9.5). Due to dilution the organic carbon and total N% values were much lower than those of clay loam soil. As in Experiment 8, there was a consistent increase in the values of almost all chemical properties (pH, SAR and ESP), and the largest increase was recorded at high salt concentration (0.75M). Unlike the clay loam soil the EC$_e$ of the treated soil was greater than the value normally considered to be non-saline (4 dSm^{-1}) especially at the high sodicity level. During the course of the experiment there was a marked decrease in SAR and ESP, as in Experiment 8 (Clay loam soil). There was also a small decrease in EC_e but pH was relatively unchanged.

Table 9.5. pH, electrical conductivity (EC_e), sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), total carbon %, total nitrogen % and texture of the soil before sowing and after harvesting

Salt applied	Control No salt	Low (0.25M,$NaHCO_3$)	High (0.75M,$NaHCO_3$)
		Before sowing	
$EC_e(dSm^{-1})$	4.4	4.6	8.0
pH (1:2.5, H_2O)	7.5	8.2	10.0
SAR	5.8	15.7	42.9
ESP	6.9	18.2	39.4

Texture

Sand total =78.5 %
2000-----------630µm = 2.8 %
630µm--------200µm =65.8 %
200µm----------63µm = 9.9 %
Silt ----------------=12.9 %
Clay --------------= 8.6 %
Class -------------- = Loamy sand (UK classification)

Total carbon %	1.75
Total N%	0.09

Salt applied	Control No salt	Low (0.25M,$NaHCO_3$)	High (0.75M,$NaHCO_3$)
		After harvesting	
$EC_e(dSm^{-1})$	1.7	3.0	6.0
pH (1:2.5,H_2O)	7.8	8.7	9.2
SAR	2.6	12.0	37.5
ESP	2.6	14.3	35.3

9.4.2.2 Visual observations

In this experiment at high sodicity, plants grown from both dry and pre-germinated seeds were late in maturing. They were harvested one week later, compared to the plants grown from transplanted seedlings. These plants also had dark green leaves and stems throughout the growth period, with dry heads, at maturity.

9.4.2.3 Survival %

The effects of sodicity and sowing method on survival % are presented in Table 9.6. The data show that unlike in the clay loam soil the survival % of plants was not significantly affected by sodicity or sowing method.

Table 9.6. Effect of low and high sodicity on survival % of Kharchia-65, under loamy sand soil condition

	Sodicity			
	Control	Low	High	Means
ESP	7	18	39	
Survival (%)				
Dry seed	100	96	96	97.6
Pre-germinated seed	100	100	89	96.4
16 day old seedlings	100	100	96	98.8
21 day old seedlings	100	100	100	100.0
Means	100.0	99.1	95.5	
Transformed data [arcsine (%/100)]				
Dry seed	1.57	1.43	1.43	1.48
Pre-germinated seed	1.57	1.57	1.24	1.46
16 day old seedlings	1.57	1.57	1.43	1.52
21 day old seedlings	1.57	1.57	1.57	1.57
Means	1.57	1.53	1.42	

	Sodicity		Method		Sodicity*Method	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
Survival %	0.061	N. S	0.071	N. S	0.124	N. S

9.4.2.4 Ion concentrations in the flag leaf sap

Table 9.7. shows the effect of sodicity on the concentration of Na^+, K^+, Ca^{2+} and Mg^{2+} ions and K^+/Na^+ ratio in the flag leaf sap. The effect of increasing sodicity was to increase Na^+, and decrease K^+, Ca^{2+}, Mg^{2+} and K^+/Na^+ ratio in the leaf sap. Sowing method had no significant effect on ion concentration, except in the case of Ca^{2+}, where transplanting of 21 day old seedlings resulted in higher Ca^{2+} than sowing dry or pre-germinated seed. The sodicity x sowing method interaction was not significant.

Table 9.7. Effect of low and high sodicity on ion concentrations and K^+/Na^+ ratio in the flag leaf sap of Kharchia-65, under loamy sand soil condition

	Sodicity			
	Control	Low	High	Means
ESP	7	18	39	
Na^+ mol m^{-3}				
Dry seed	3	28	193	74.3
Pre-germinated seed	3	16	142	53.5
16 day old seedlings	3	17	178	66.0
21 day old seedlings	3	26	173	67.5
Means	3.0	21.6	171.5	
K^+ mol m^{-3}				
Dry seed	269	243	151	220.6
Pre-germinated seed	272	318	187	258.6
16 day old seedlings	291	258	172	240.1
21 day old seedlings	265	303	181	249.5
Means	274.1	280.0	172.5	
K^+/Na^+ ratio				
Dry seed	111.0	10.3	0.8	40.5
Pre-germinated seed	95.3	27.0	1.7	41.2
16 day old seedlings	118.0	22.1	1.1	46.9
21 day old seedlings	99.0	16.0	1.1	38.6
Means	105.5	18.8	1.1	
Ca^{2+} mol m^{-3}				
Dry seed	26	13	8	15.2
Pre-germinated seed	26	14	6	15.1
16 day old seedlings	29	14	12	18.2
21 day old seedlings	39	23	9	23.7
Means	29.8	15.8	8.6	
Mg^{2+} mol m^{-3}				
Dry seed	23	18	10	16.9
Pre-germinated seed	19	19	10	15.8
16 day old seedlings	21	18	16	18.2
21 day old seedlings	25	21	16	20.8
Means	21.7	19.10	13.0	

	Sodicity		Method		Sodicity*Method	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
Na^+	10.0	20.0* * *	11.3	N. S	20	N. S
K^+	17.0	35.0* * *	20.0	N. S	34.1	N. S
K^+/Na^+	9.1	19.0* * *	11.0	N. S	18.3	N. S
Ca^{2+}	2.2	4.5* * *	2.5	5.2* *	4.4	N. S
Mg^{2+}	2.1	4.3* *	2.4	N. S	4.2	N. S

9.4.2.5 Yield and yield components

The effects of sodicity on yield and yield components are presented in Table 9.8. The results showed that the plants grown at low ESP were not significantly different from the control in grain yield and most of the yield components. However, the effects of

Table 9.8 (a). Effect of low and high sodicity and sowing methods on grain yield and yield components of Kharchia-65 under loamy sand soil condition

	Sodicity			Means
	Control	Low	High	
ESP	7	18	39	
No. of ears/plant				
Dry seed	1.3	1.4	1.1	1.26
Pre-germinated seed	1.7	1.7	1.2	1.53
16 day old seedlings	1.6	1.8	1.3	1.58
21 day old seedlings	2.4	1.6	1.8	1.90
Means	1.72	1.62	1.36	
No. of grains/plant				
Dry seed	31	30	16	25.3
Pre-germinated seed	30	31	7	22.8
16 day old seedlings	31	32	26	29.7
21 day old seedlings	37	33	26	32.2
Means	32.2	31.6	18.7	
Grain dry wt/plant (mg)				
Dry seed	1586	1469	654	1236.3
Pre-germinated seed	1373	1605	326	1101.1
16 day old seedlings	1617	1578	1121	1438.5
21 day old seedlings	1772	1637	1129	1512.9
Means	1587.1	1572.1	807.4	
Grain dry wt/m^2 (g)				
Dry seed	991	891	400	760.5
Pre-germinated seed	858	1002	182	680.8
16 day old seedlings	1010	986	681	892.6
21 day old seedlings	1108	1023	708	945.4
Means	991.9	975.5	492.1	
1000 grain wt (g)				
Dry seed	53	50	41	47.8
Pre-germinated seed	46	52	36	44.6
16 day old seedlings	53	47	41	46.9
21 day old seedlings	48	49	41	46.2
Means	50.0	49.2	39.8	

	Sodicity		Method		Sodicity*Method	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
No. of ears/p	0.156	N. S	0.179	0.367*	0.311	N. S
No. of grains/p	3.7	7.4* *	4.2	N. S	7.3	N. S
1000 grain wt	2.8	5.7* *	3.3	N. S	5.6	N. S
Grain wt/p	197.9	401.6* * *	228.5	N. S	395.7	N. S
Grain wt/m^2	125.0	253.0* * *	144.0	N. S	250.0	N. S

Table 9.8 (b). Effect of low and high sodicity on straw yield /plant and /m^2 and harvest index (%) of Kharchia-65 under loamy sand soil condition

	Sodicity			
	Control	Low	High	Means
ESP	7	18	39	
Straw dry wt/plant (mg)				
Dry seed	1680	1462	974	1372.2
Pre-germinated seed	1859	1794	583	1411.7
16 day old seedlings	1524	1726	1311	1520.1
21 day old seedlings	1783	1457	1312	1517.5
Means	1711.4	1609.8	1044.9	
Straw dry wt/m^2 (g)				
Dry seed	1050	885	580	839.8
Pre-germinated seed	1662	1121	330	871.0
16 day old seedlings	952	1079	795	941.9
21 day old seedlings	1114	911	820	948.3
Means	1069.6	998.8	632.5	
Harvest Index (%)				
Dry seed	49	50	40	46.0
Pre-germinated seed	43	49	27	39.7
16 day old seedlings	51	46	44	47.2
21 day old seedlings	50	52	45	48.8
Means	48.3	49.1	38.8	

	Sodicity		Method		Sodicity*Method	
	S. E. D.	L. S. D.	S. E. D.	L. S. D.	S. E. D.	L. S. D.
Straw wt/p	194.0	393.0* *	224.0	N. S	387	N. S
Straw wt/m^2	122.0	248.0* *	141.0	N. S	244	N. S
H. I (%)	2.8	5.6* *	3.2	6.5* *	5.5	N. S

high sodicity were significant. Plants grown at high sodicity had fewer grains, lower grain dry weight per plant and per m^2, and lower 1000 grain weight compared to the control plants. In the case of straw yield, plants grown at high sodicity had lower straw dry weight/plant and /m^2. The effects of sodicity on grain dry weight were greater than its effects on straw dry weight, so that harvest index also decreased. Although the effects of sowing method and the sowing method x sodicity interaction on yield and yield components were not significant, grain yield/plant and /m^2 at high sodicity were greater in transplanted seedlings than in plants grown from dry and pre-germinated seed, mainly due to the transplanted seedlings having more grains/plant. High sodicity decreased grain yield /plant of the plants established from dry and pre-germinated seed by 59 and 76 %

respectively. The corresponding decreases in grain yield per plant of the plants from 16 and 21 day old seedlings were 31 and 37 % respectively. At high sodicity, plants from transplanted seedlings also had higher straw dry wt/plant and /m^2 and higher harvest index than control plants.

9.4.2.6 Effects of sodicity, methods of sowing and soil type on ion concentration yield and yield components (combined analysis)

To test whether the effects of the different treatments (sodicity and methods of sowing) were different in the different soils, a separate analysis of variance was performed on the combined data from the two soil types (Table 9.9a, b, c and d). This analysis is not strictly correct, as the pots of the two soils were on opposite sides of the growth chamber, and not randomised together. However, the method of sowing treatments were the same, and the sodicity levels were not markedly different in the two experiments. The ESP values before sowing in the control, low and high sodicity treatments were 5, 20 and 40 in Experiment 8 and 7, 18 and 39 in Experiment 9 respectively.

In the analyses of the data for grain yield/plant, grain yield/m^2, ears/plant and grains/plant, the main effects of sodicity and method of sowing were significant, but the effects of soil and all interactions were not significant. This means that for these parameters, the effects of sodicity and method of sowing were same in both soils. (Table 9.9c). In the ANOVA of the data for survival %, the main effects of sodicity and method of sowing were significant, and the method of sowing x sodicity interaction was also significant. However, the effects of soil type and all other interactions were again not significant (Table 9.9d).

In the case of straw yield/plant, per m^2 and harvest index %, the main effects of sodicity were significant, but the effect of soil was only significant in straw yield/plant, and the effect of method of sowing was significant only for harvest index. The sodicity x method of sowing interaction was significant for all these three parameters (Table 9.9d), but all other interactions were not significant. This indicates that the effects of sodicity were same on both soils.

The main effects of sodicity were significant for all (Na^+, K^+, Ca^{2+} and Mg^{2+}) ion concentrations and K^+/Na^+ ratios (Table 9.9a). However, the effects of method of sowing were only significant for Ca^{2+} and Mg^{2+}. The effect of soil type was significant only in the case of K^+.

The sodicity x soil, sowing method x soil and sodicity x sowing method x soil interactions were not statistically significant in almost all the cases and therefore these values are not presented here.

Averaged over all sowing methods and two soils (Table 9.9a), low sodicity had no adverse effect on survival, grain and straw yield and all yield components, but high sodicity significantly decreased plant survival, grain and straw yield and almost all yield components. Increasing sodicity significantly increased flag leaf Na^+ and significantly decreased Ca^{2+} and K^+/Na^+ ratio. Significant decreases in K^+ and Mg^{2+} were only observed at high sodicity, but not at low.

Table 9.9 (a). Mean effects of sodicity on yield, yield components, ion concentration and K^+/Na^+ ratio. Values are the means of 4 sowing methods and two soils

Parameter	Sodicity			Significance level	
	Control	Low	High	S. E. D.	L. S. D.
Yield and yield components					
Survival % (arcsine value)	1.57	1.55	1.33	0.045	0.088* * *
No. of grains/plant	33.2	33.1	17.9	2.63	5.20* * *
Grain wt/plant (g)	1621.4	1699.0	799.0	430.0	850.0* * *
Straw wt/plant (mg)	1758.8	1762.2	1042.2	131.2	260.0* * *
1000 grain wt(g)	49.2	51.2	42.0	1.70	3.36* * *
No. of ears/plant	1.8	1.8	1.4	0.13	0.26*
Grain yield/m^2 (g)	1013.3	1058.9	484.6	85.53	169.34* * *
Straw yield/m^2 (g)	1099.1	1097.7	622.1	82.00	162.20* * *
Harvest index (%)	47.9	48.8	38.5	3.54	7.01* * *
Ion concentration in flag leaf sap					
Na^+ mol m^{-3}	2.6	22.9	184.0	7.30	14.41* * *
K^+ mol m^{-3}	263.0	269.8	160.0	12.03	24.00* * *
Ca^{2+} mol m^{-3}	29.5	16.2	7.6	1.90	3.74* * *
Mg^{2+} mol m^{-3}	22.4	19.0	12.0	2.10	4.13* * *
K^+/Na^+	114.0	17.4	1.1	7.05	14.00* * *

Averaged over all sodicity treatments and two soils (Table 9.9b), plant survival, number of grains, grain wt per plant and per m^2 and harvest index were significantly higher, whereas other parameters were not significantly higher in plants established from transplanted seedlings than seed sown plants. Transplanted (21 day old) plants had significantly more Ca^{2+} and Mg^{2+} ions than seed sown plants.

Although it was non significant in all cases, averaged over all sodic treatments and method of sowing (Table 9.9c), plants grown in clay loam had slightly higher values of all traits than the plants grown in loamy sand soil. Except K^+, which was higher in loamy sand soil plants, in other ions there were no marked and significant differences between two soils. However averaged overall for the two soils, the interaction of sodicity x sowing was not significant in grain yield /m^2, compared to the transplanted plants. High sodicity generally had adverse effects on survival %, grain and straw yield /m^2 of pre-germinated and dry seed sown plants (Table 9.9d).

Table 9.9 (b). Main effects of sowing methods on yield, yield components, ion concentration and K^+/Na^+ ratio. Values are the means of 3 sodicity levels and two soils

	Method				Significance level	
	Seed sowing		Transplanting			
Parameter	D-S	P-G	16 D-T	21 D-T	S. E. D.	L. S. D.
	Yield and yield components					
Survival % (arcsine)	1.44	1.40	1.54	1.57	0.052	0.103* *
No. of grains/plant	24.8	22.4	31.6	33.5	3.04	6.01* *
Grain wt/plant (g)	1212.0	1108.0	1582.7	1580.4	160.0	312.0* *
Straw wt/plant (mg)	1356.3	1427.7	1670.0	1630.1	151.5	N. S
1000 grain wt.(g)	48.2	45.5	49.2	47.0	1.96	N. S
No. of ears/plant	1.4	1.7	1.7	1.9	0.15	0.30*
Grain yield/m^2(g)	753.0	683.0	986.0	988.0	98.75	195.55* *
Straw yield./m^2 (g)	830.0	870.0	1040.0	1019.0	82.00	N. S
Harvest index (%)	45.3	39.0	48.0	48.3	2.17	4.30* * *
	Ion concentration in flag leaf sap					
Na^+ mol m^{-3}	75.6	60.0	65.0	80.0	8.40	N. S
K^+ mol m^{-3}	222.0	228.3	234.0	239.0	10.30	N. S
Ca^{2+} mol m^{-3}	15.0	15.0	18.2	23.4	2.20	4.33* * *
Mg^{2+} mol m^{-3}	16.3	14.8	19.0	21.0	1.66	3.30* *
K^+/Na^+	48.0	44.3	46.0	38.2	8.15	N. S

Table 9.9 (c). Mean effects of soil type on yield, yield components, ion concentration and K^+/Na^+ ratio. Values are the means 4 sowing methods and 3 sodicity treatments

	Soils		Significance level	
Parameter	Clay loam	Loamy sand	S. E. D.	L. S. D.
	Yield and yield components			
Survival % (arcsine value)	1.46	1.50	0.036	N. S
No. grains/plant	28.6	27.5	2.15	N. S
Grain wt./plant (g)	1.4	1.3	0.11	N. S
Straw wt./plant (mg)	1587.0	1455.4	107.3	N. S
1000 grain wt.(g)	48.4	46.4	1.39	N. S
No. ears/plant	1.8	1.6	0.34	N. S
Grain yield/m^2 (g)	885.0	820.0	70.00	N. S
Straw yield/m^2	979.0	900.0	67.00	N. S
Harvest index (%)	44.7	45.5	1.54	N. S
	Ion concentrations in flag leaf sap			
Na^+ mol m^{-3}	74.3	65.4	5.94	N. S
K^+ mol m^{-3}	219.4	242.0	9.82	19.45*
Ca^{2+} mol m^{-3}	17.5	18.1	1.55	N. S
Mg^{2+} mol m^{-3}	17.2	17.9	1.18	N. S
K^+/Na^+	46.5	41.8	5.76	N. S

Table 9.9 (d). Main effects of low and high sodicity and methods of sowing on survival %, grain yield, straw yield/m^2 and H. I. Values are the means of two soils

	Parameters			
	Survival % (arcsine value)	Grain yield/m^2 (g)	Straw yield/m^2 (g)	H.I (%)
Dry seed				
Control	1.57	1030.2	1068.0	49.0
Low	1.50	907.0	959.0	48.3
High	1.24	321.2	465.1	39.0
Pre-germinated seed				
Control	1.57	878.0	1188.2	43.0
Low	1.57	1061.0	1182.0	48.0
High	1.02	109.4	239.3	26.1
16 day old seedlings				
Control	1.57	1042.0	1012.2	51.0
Low	1.57	1119.2	1188.0	48.0
High	1.50	797.0	919.0	45.3
21 day old seedlings				
Control	1.57	1103.4	1129.0	49.4
Low	1.57	1148.4	1063.0	51.4
High	1.57	711.2	865.0	44.1
S. E. D.	0.090	171.05	471.30	3.76
L. S. D.	0.180* * *	N. S	933.10* *	7.45*

9.5 Discussion

As both the experiments were identical in all cases, apart from soil type, the results are discussed together.

9.5.1 Soil

The soil analysis results presented in Table 9.1 and Table 9.5 show that as in earlier experiments (Chapter 6), adding $NaHCO_3$ to soil resulted in increases in pH, SAR and ESP. The increases were most pronounced in the treatment which was sprayed with the highest concentration of $NaHCO_3$.

It can also be seen from Table 9.1 and Table 9.5 that the clay loam soil had high and the loamy sand soil had lower organic matter and N content, while there were smaller differences between the two soils in other chemical properties such as, pH, SAR and ESP values following the application of $NaHCO_3$.

The soil data also showed that the values of almost all chemical soil properties did not remain stable during the course of study. SAR and ESP and to some extent EC_e and pH were lower at harvest than they were at sowing. Such types of change between sowing and harvest have also been recorded in earlier experiments (Chapters 6 and 7). These changes possibly occurred due to leaching as a result of watering during the course of study.

As in the experiments reported in Chapter 5 (Section 5.7.1.1), on the basis of SAR and ESP, the soils used in these 2 experiments are classified as (1) non-saline and non-sodic (control soil), moderately sodic (low ESP treatment) and strongly sodic (high ESP treatment).

9.5.2 Plants

9.5.2.1 General appearance and survival of plants at maturity

In both the experiments, at high ESP, the plants established from dry and pre-germinated seed were similar to one another in general appearance, i.e. they were lush green with weak stems and late in maturity (Section 9.4.1.1 and Section 9.4.1.2). However, sowing dry seed resulted in plants with slightly better appearance than sowing pre-germinated seed. In the high ESP treatment the transplanted plants appeared much healthier, were more advanced in maturity, and were similar in appearance to those in the control.

This shows that high sodicity delayed maturity of plants in the seed sowing treatments but not in the transplanting treatments. This delay in maturity is not feasible for tropical countries like Pakistan, especially in Sindh province, where hot and dry southern winds during harvest in April often result in immature seed, leading to great yield loss. The delay in harvest also creates problems to prepare land for the next seasons crop, especially cotton.

The results of this study showed that sodicity significantly decreased the survival % of mature plants at high ESP but not at low ESP in clay loam soil (Tables 9.2 and 9.9e), and not in loamy sand soil (Tables 9.6 and 9.9e). Sowing of dry and pre-germinated seed resulted in significantly lower survival of plants in clay loam soil and non significantly lower survival in loamy sand soil. There are two possible reasons for the increased survival of plants sown as transplanted seedlings. Firstly, they passed through the sodicity-sensitive germination stage in a non-sodic medium (compost). Secondly, their better developed root system at establishment may have promoted their growth and survival. It is possible that the roots of transplanted seedlings began to elongate in the soil more easily than the roots of plants established from dry and pre-germinated seed. At high ESP some of the seeds did not germinate, and some emerged seedlings from dry and pre-germinated seeds died quickly and a few plants had no ears at maturity so that survival % was significantly lower. This is possibly because high sodicity might have prevented some emerged seedlings from utilising nutrients from the soil after their own small seed reserves became exhausted, so that they did not survive as well as the transplanted plants. High survival of plants following transplanting compared to direct sowing was possibly due to the uptake of nutrients by seedlings through well developed root systems, which might have enabled plants to make successful growth in the presence of the adverse effects of high sodicity. Large adverse effects of sodicity on the roots of wheat seedlings established from seed sown method have also been observed in Experiment 2 (Chapter 5). This also suggests that the potential for successful growth and survival possibly began at these early stages. Although the performance of transplanted seedlings was higher in the control soil, the remarkable improvement of transplanted seedlings in sodic soils can be assumed to be an important feature of the transplanting method of sowing. Further experiments are required to determine if such responses are observed under field conditions. The costs and time involved in transplanting may preclude the use of this technique by farmers.

Table 9.9 (e). Summary table showing the effects of two soils and 4 sowing methods on some important plant parameters at high sodicity. - and shows the % decrease over control respectively

	Clay loam soil		Loamy sand soil	
	Control (Actual value)	High ESP (% change)	Control (Actual value)	High ESP (% change)
Survival %				
Dry seed	100	-17.6	100	- 3.6
Pre- germinated	100	- 35.7	100	-10.7
16 day old seedlings	100	0.0	100	- 3.6
21 day old seedlings	100	0.0	100	0.0
Grain yield/plant (g)				
Dry seed	1.7	- 74.4	1.6	- 59.1
Pre- germinated	1.4	- 91.7	1.4	- 76.4
16 day old seedlings	1.7	- 16.0	1.6	- 31.0
21 day old seedlings	1.8	- 36.0	1.8	- 37.2
Leaf sap Na^+ (mol m^{-3})				
Dry seed	2.2	211	2.6	193
Pre- germinated	2.0	178	3.1	142
16 day old seedlings	2.2	157	2.9	178
21 day old seedlings	2.6	241	3.4	173
Leaf sap K^+ (mol m^{-3})				
Dry seed	276.1	- 53.1	269.0	- 44.0
Pre- germinated	216.0	- 34.4	271.5	- 31.1
16 day old seedlings	255.0	- 30.0	291.0	- 41.0
21 day old seedlings	261.0	- 47.0	265.3	- 31.9
Leaf sap Ca^{2+} (mol m^{-3})				
Dry seed	24.5	- 78.6	25.7	- 70.9
Pre- germinated	25.5	- 77.5	25.7	- 76.7
16 day old seedlings	29.7	- 73.1	29.0	- 59.0
21 day old seedlings	37.0	- 79.0	39.0	- 77.0
Leaf sap Mg^{2+} (mol m^{-3})				
Dry seed	22.0	- 61.4	22.8	- 54.9
Pre- germinated	17.7	- 53.2	18.5	- 45.9
16 day old seedlings	25.3	- 44.7	20.8	- 24.0
21 day old seedlings	26.8	- 58.00	25.0	- 34.8

9.5.2.2 Yield and yield components

It can be seen from the results presented in Tables 9.4a,b and Table 9.8a,b) that in clay loam soil low sodicity had no adverse effects on plants. High sodicity had large adverse effects on grain and straw yield and all yield components in both soils (Table 9.9e).

Averaged over all soil treatments, in clay loam soil the transplanted plants had significantly more grains and non-significantly more ears, so that the grain yield per plant, grain and straw yield per m^2 and harvest index were significantly higher in transplanted plants than in seed sown plants. Although, the straw weight per plant of transplanted plants was also higher in clay loam soil, the difference was statistically non significant. However in the loamy sand soil, the results were slightly different. Although yield and all yield components except 1000 grain weight were higher in transplanted plants, differences were significant only in number of ears and harvest index. This suggests that although it was effective in both soils, generally in all sodicity treatments the transplanting method of sowing was slightly more effective in clay loam soil than in loamy sand soil. Except for straw yield per m^2 in clay loam soil, the interaction of sodicity x sowing method was non significant in all cases in both soils. Although the response was greater in clay loam soil, due to more and heavier grains, in the high ESP treatment the transplanted plants gave higher grain and straw yield than the plants established from dry and pre-germinated seed in both soils. When seeds were sown directly into sodic soils, the plants grew with difficulty, hence they had low yield compared to the transplanted plants. The reasons for this could be improved root growth as stated in Section 9.5.2.1. By looking at the % decreases presented in Table 9.9e, in both experiments pre-germinated seed gave the lowest yield and showed the largest % decrease in yield at high sodicity. The % decrease in grain yield with dry seed was less than with pre-germinated seed, but much greater than with transplanted seedlings.

Measurements of ion concentrations were made on the flag leaf, because of its importance as a source of carbohydrate for grain filling. However, as ion concentrations in salt-affected plants are higher in older leaves than younger leaves, the trends may have been different in these plants if they had been analysed.

The large decreases in survival %, grain and straw yield and yield components at high ESP in both experiments were associated with higher Na^+ and lower K^+, Ca^{2+} and Mg^{2+} concentrations and lower K^+/Na^+ ratio (Table 9.3 and Table 9.7). There was no evidence of a decrease in Na^+ and an increase in K^+/Na^+ ratio in transplanted plants, compared to seed sown plants. These results suggest that the high yield of transplanted plants was not due to low uptake of toxic ions. The improved survival, grain and straw yield in transplanted plants in the high sodicity treatment was also associated with higher concentrations of Ca^{2+} and Mg^{2+}in transplanted plants than in seed sown plants. Similar results have also been presented by Farooq *et al.* (1995), who reported that although grain and straw yields were higher in transplanted plants, either at seedling stage or heading or at maturity and, the transplanted plants tended to have higher Na^+ and lower K^+/Na^+ ratio than plants grown by broadcasting seeds in a saline field.

9.5.2.3 Combined analysis

In the combined ANOVA differences between soil types (Table 9.9c), and the interaction of treatments with soil type were non significant (data not shown). Although, there were large differences between two soils for N %, organic matter % and clay content, the differences in the control plants for grain yield, ion concentrations and other parameters were very small.

In the separate ANOVAS, the effect of sowing method on grain wt/plant was significant in clay loam soil but not in loamy sand soil. However, when the combined ANOVA was performed, the error degrees of freedom were increased and the data showed significant effects of sowing method on grains/plant, ears/plant, grain wt/plant and grain wt/m^2. Table 9.9e suggests that the effects of high sodicity on survival and grain yield with seed sowing were greater in clay loam than loamy sand and greater with pre-germinated than dry seed. However these effects were not strongly associated with any trends in K^+ and Na^+ uptake.

9.6 Conclusions

- High sodicity significantly decreased survival, grain and straw yield in both soils.
- As sodicity increased the concentration of Na^+ increased and Ca^{2+} and Mg^{2+} and K^+/Na^+ ratio in flag leaf sap decreased in both soils.
- The differences between soils for ion concentrations in flag leaf sap in almost all soil treatments were small and non significant.
- Plants established from pre-germinated seed proved to be more sensitive to sodicity than plants established from dry seed.
- Transplanted plants showed good survival and gave higher yield, and had more Ca^{2+} and Mg^{2+} in flag leaf sap than dry and pre-germinated seed sown plants in all soil treatments including the control.

- Transplantation of 16 day old seedlings in the high ESP treatment gave higher yield, they also had less Na^+ and more K^+, Mg and higher K^+/Na^+ ratio than 21 day old seedlings in clay loam soil.
- In loamy sand soil 21 day old seedlings showed slightly better performance than 16 day old seedlings, generally in all soil treatments, but especially in the high ESP treatment. They had more ears, higher straw weight per plant and more Ca^{2+} in flag leaf sap.
- Under experimental conditions plants established from transplanted seedlings gave higher survival and yield than plants established from seed. Further experiments are required to evaluate this technique on sodic soils under field conditions.

CHAPTER 10

Effect of soil salinity and sodicity on seedling emergence, ion uptake, growth, survival and yield of two durum (Triticum turgidum L.) wheat genotypes with and without gene (Kna1)

CHAPTER 10

Effects of soil salinity and sodicity on seedling emergence, ion uptake, growth, survival and yield of two durum wheat (*T. turgedium L.*) genotypes with and without gene (Kna1)

10.1 Introduction

Scientists are currently investigating the chromosomal location of genes which confer resistance to salt, heat shock and diseases. It is evident from recent reports, which have been presented by some workers (Gorham, 1992; Longnecker, 1994) that it is the D genome that carries a (salt-resistant) K^+/Na^+ discriminating gene (Kna1) in the modern hexaploid wheat containing the A, B and D genomes. The exact location of this gene is on the long arm of chromosome 4D (Gorham *et al.*, 1987; Shah *et al.*, 1987).

Hexaploid wheat is classified as moderately salt tolerant (Maas and Hoffman, 1977) but the tetraploid (durum) wheat (BBAA) is considered salt-sensitive due to lack of chromosome 4D. Dvorak *et al.* (1994) recombined the 4D chromosome with chromosome 4B of durum wheat to make it salt-resistant.

Salinity is a more complex phenomenon than a simple increase in Na^+ and Cl^- concentrations (Gorham, 1992). In saline soil together with Na^+ and Cl^- other ions (Ca^{2+}, Mg^{2+}, SO_4^{2-} and B) may be present in excessive amounts. On the other hand in addition to excessive and toxic amounts of Na^+, CO_3^{2-}, and HCO_3^-, plants under sodic soil conditions also face other problems, e.g. high pH, collapsed soil structure, impeded drainage and anaerobic soil conditions. Different salts may thus differently influence the growth of plants (Moustafa *et al.*, 1966).

The experiments reported in this Chapter studied the performance of durum wheat genotypes with and without K^+/Na^+ discriminating gene (Kna1) under saline and sodic soil conditions. The aim of these experiments was to study differences between the genotypes in seedling emergence, ion uptake, growth, survival and yield under saline and sodic soil conditions.

Hence in this study both types of genotype (with and without K^+/Na^+ discriminating gene) were tested in a series of artificially prepared saline soils containing a mixture of NaCl, $CaCl_2$ and $MgCl_2$ and sodic soils containing $NaHCO_3$ salt. The first experiment was conducted to compare their seedling emergence %, while the second experiment was conducted to compare their seedling emergence %, ion uptake, growth and yield. There have been several reports on the performance of these genotypes under saline conditions, usually in hydroponic culture (Gorham *et al.*, 1997) but few of their performance under saline or sodic soil conditions.

10.2 Objectives

This study was conducted with the following specific objectives:

(1). To study the effects of sodicity (using $NaHCO_3$), and salinity (using a mixture of NaCl, $CaCl_2.2H_2O$ and $MgCl_2$ salts) on seedling emergence, ion uptake, growth, yield and survival %;

(2). To investigate differences between genotypes in seedling emergence, ion uptake, growth, yield and plant survival % under salinity and sodicity;

(3). To determine whether the Kna1 gene, which allows the plant to discriminate between Na^+ and K^+ and thereby improves plant performance on saline soils, is also useful under sodic conditions.

10.3 Materials and methods

Three durum wheat genotypes ($R112^+$, $R21^-$ and $R23^-$) were tested in two experiments with 3 salinity (120, 150 and 180 $mmol_c\ l^{-1}$) and 3 sodicity levels (120, 150 and 180 $mmol_c\ l^{-1}$) together with a control. The first experiment was conducted up to 20 days for recording seedling emergence using two genotypes ($R112^+$and $R21^-$). In the second experiment genotypes $R112^+$and $R23^-$ were grown up to maturity, and their seedling emergence, ion uptake, growth and yield were recorded. $R112^+$ has the Kna1 discriminating gene and $R21^-$ and $R23^-$ do not.

10.3.1 Soil preparation

These experiments were conducted using the same Caeglanmore clay loam soil as that used in Experiment 4, which is reported in Chapter 5 (section 5.4.1.1). To prepare soils with different levels of salinity (120, 150 and 180 $mmol_c\ l^{-1}$) NaCl, $CaCl_2$ and $MgCl_2$ salts were mixed in equal proportion, i.e. 40 $mmol_c\ l^{-1}$ of each salt to give 120 $mmol_c\ l^{-1}$, 50 $mmol_c\ l^{-1}$ of each salt to give 150 $mmol_c\ l^{-1}$ and 60 $mmol_c\ l^{-1}$ of each salt to give 180 mmol$_c$ l^{-1}. The salt mixtures were then mixed with the dry soil, as described in Chapter 3. To prepare soils with different levels of sodicity (120, 150 and 180 mmol$_c$ l^{-1}), the amount of $NaHCO_3$ salt to add was calculated following the same method of calculation as in the saline soil treatments, but the application of this salt (spray and incubation method) was the same as reported for sodic soil preparation in Chapter 3 (Section 3.1).

10.3.2 Seed multiplication, sowing and seedling emergence

So as to have sufficient seeds, the genotypes R112$^+$, R21$^-$ and R23$^-$ were initially multiplied in soil filled pots placed in a glasshouse during 1997. Both experiments were conducted in a split plot design with 4 replicates. Salt treatments constituted the main plots and genotypes constituted the subplots. To conduct the first experiment, the multiplied seeds of R112$^+$ and R21$^-$ were sown in pots (35 x 24 surface and 19.5 cm depth) on 30. 11. 1997, at a plant to plant distance of 4 cm. Two seeds were sown in each position with 10 positions for each genotype per pot. This resulted in a total of 40 seeds per pot. Seedling emergence was recorded 10, 15 and 20 DAS. Initially the pots of this experiment were placed in a glasshouse, but these pots were then moved into a walk-in growth room at 21 DAS. This experiment was terminated after having recorded the final seedling emergence because of a mechanical fault in the temperature regulating system in the growth chamber. The seedlings of the first experiment were removed from the pots in order to start a second experiment using the soil and pots.

In the second experiment seeds of R112$^+$ and R23$^-$ were sown on 6. 1. 1998 as described for the first experiment. Seedling emergence was recorded at 6, 10 and 15 DAS. After recording the final emergence data, seedlings were thinned to single plants in each position. Seedling emergence % was calculated using the following formulae:

$$\text{Seedling emergence \%} = \frac{\text{number of seedlings that emerged}}{\text{total number of seeds sown}} \text{x100}$$

Transformed value = Seedling emergence %/ 100, value transformed into arcsine

10.3.3 Growth conditions

The first experiment was conducted in a glasshouse, at Henfaes Agricultural Research Station, University of Wales, Bangor, UK, during the months of November and

December 1997. The plants of the second experiment were initially grown in a walk-in growth room, set at 18 ^{0}C day and 9 ^{0}C night temperatures, 65% RH with a photoperiod of 16 hours. These, pots were moved into a glasshouse 2 months after sowing (5. 3. 1998). Temperature in the glasshouse was not controlled, but supplementary lighting was provided from 250 watt sodium lamps, to extend the daylength to 16 hours/day.

10.3.4 Irrigation and fertiliser

All pots were regularly irrigated with tap water and nutrients were applied as Phostrogen fertiliser using the same rate and method as in Chapter 6 (Section 6.3.3).

10.3.5 Flag leaf sampling, extraction and chemical analysis of sap

In the second experiment, fully expanded flag leaves of two plants per genotype from each pot of the control, 150 mmol$_c$ l^{-1} saline and 150 mmol$_c$ l^{-1} sodic soil treatments were sampled. In R23^{-}, but not in R112^{+}, the different treatments reached the flag leaf fully expanded stage on different days. In the control and 150 mmol$_c$ l^{-1} saline soil treatments, the flag leaves of R23^{-} genotype expanded earlier, hence the sampling was done 10 days earlier (5. 3. 1998) than for the sodic treatments for this genotype. Although the flag leaves of genotype R112^{+} reached full expansion later than R23^{-}, sampling of the flag leaves from this genotype was done on the same day, 18. 3. 1998 in all three soil treatments. These samples were placed in Eppendorf tubes and stored at -10 ^{0}C in a freezer. Leaf sap was extracted and analysed for Na^{+}, K^{+}, Ca^{2+}, Mg^{2+} and Cl^{-} as described in the Chapter 3 (Section 3.2). At 58 DAS the number of fully expanded leaves on the main stem and number of tillers per plant were recorded using all plants in each pot.

10.3.6 Final harvest

The plants were harvested at maturity on 20. 5. 1998 by cutting plants at soil level. Plants that had previously been sampled from the control, 150 mmol$_c$ l^{-1} saline and 150 mmol$_c$ l^{-1} sodic treatments for chemical analysis and those without ears in all soil treatments were not incorporated in the yield data. After measuring plant height, mature ears were separated from straw but the green ears were left intact. Mature ears and straw along with the green ears of survived plants were placed in separate paper bags for drying at 82 ^{0}C for 48 hr. The grains from each sample were threshed, cleaned and weighed. Number of mature ears, number of grains, and straw dry weight were determined. Survival %, harvest index %, grain and straw dry wt/plant and m^2 were calculated from the recorded data using the following formulae:

$$\text{Survival \%} = \frac{\text{number of plants that survived with ears at maturity}}{\text{number of plants per pot left after thinning}} \times 100$$

$$\text{Grain weight/plant} = \frac{\text{grain weight per pot}}{\text{number of plants that survived with ears at maturity}}$$

$$\text{Grain or straw weight/m}^2 = \frac{\text{Grain or straw weight per pot}}{\text{Pot area (m}^2\text{)}}$$

10.3.7 Soil analyses and calculations

Individual soil samples from each treatment before sowing and composite samples of soil treatments after harvesting were collected. Soil samples were air dried, sieved and prepared to analyse the physical (texture) and chemical soil properties (Na^+, K^+, Ca^{2+} Mg^{2+}, pH and EC_e, N and C).

10.3.8 Statistical analyses

All plant data collected were statistically analysed by using ANOVA (Minitab statistical package) procedures appropriate for split plot designs. Salt treatments constituted the subplots. Prior to ANOVA analyses, the emergence % and survival % data were transformed into arcsine (%/100) values. To assess significant differences between the means of: (a) salt treatments, (b) genotypes, (c) genotypes within one salt treatment and (d) salt treatments for the same or different genotypes, the standard error for the difference between means (S. E. D.) and the least significant difference (L. S. D.) were calculated using the following formulae:

Standard error of the difference between means and least significant difference:

(1) **between means of salt treatments**

$$\text{S. E. D.} = \sqrt{\frac{2xError_a}{rxb}}$$

L. S. D. = S. E. D x t value (Edf$_a$ at 5% level of significance).

Where:

r = no. of blocks (replication 4)

b = no. of levels of treatments (genotypes 2)

Error$_a$ = Main plot Error mean square

(2) **between means of genotypes**

$$\text{S. E. D.} = \sqrt{\frac{2xError_b}{rxa}}$$

L. S. D. = S. E. D x t value (Edf$_b$ at 5% level of significance).

Where:

a = main factor (7 salt treatments)

Error $_b$ = Sub plot Error mean square

(3) **between means of genotypes within one salt treatment**

$$\text{S. E. D.} = \sqrt{\frac{2xError_a}{r}}$$

L. S. D. = S. E. D x t (Edf$_b$ at 5% level of significance).

(4) **between means of salt treatments for the same or different genotypes**

$$\text{S. E. D.} = \sqrt{\frac{2[(b-1)Error_b xError_a]}{rxb}}$$

L. S. D. = S. E. D x t value (Edf$_b$ at 5% level of significance).

10.4 Results

10.4.1 Effects of saline and sodic salts on chemical soil properties recorded before sowing (Experiment 10) and after harvest (Experiment 11)

Table 10 shows the properties of the soil in this study. The pH, EC$_e$, ESP, SAR, total carbon % and N % values of the control soil before sowing and after harvest were typical of fertile, non-saline and non-sodic soils. However, these soil properties showed a marked change in response to applied saline and sodic salts. Addition of sodium, calcium and magnesium chlorides resulted in a large increase in electrical conductivity but not in SAR and ESP compared to the sodic soil treatments. pH was lower in the saline and higher in the sodic soil treatments than in the control. Electrical conductivity showed a slight increase with increasing amounts of $NaHCO_3$ salt, but pH, SAR and ESP showed much large increases with increasing amount of $NaHCO_3$ salt.

Table 10. pH, electrical conductivity (EC_e), sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), total carbon, total nitrogen and texture of the soil before sowing and after harvest

Treatment	Salt applied	pH	EC_e (dSm^{-1})	SAR	ESP
Before sowing					
Control	= No salt	6.6	2.0	4.0	5.0
Saline	($NaCl + CaCl_2 + MgCl_2$)				
(1)120 $\mathrm{mmol_c\,l^{-1}}$	= 40 + 40 + 40	5.5	12.3	10.5	12.6
(2)150 $\mathrm{mmol_c\,l^{-1}}$	= 50 + 50 + 50	5.0	16.5	7.7	9.3
(3)180 $\mathrm{mmol_c\,l^{-1}}$	= 60 + 60 + 60	5.0	19.0	8.8	10.7
Sodic	($NaHCO_3$)				
(1)120 $\mathrm{mmol_c\,l^{-1}}$	= 120	8.0	3.2	33.8	33.1
(2)150 $\mathrm{mmol_c\,l^{-1}}$	= 150	8.6	4.2	45.4	40.3
(3)180 $\mathrm{mmol_c\,l^{-1}}$	= 180	8.9	5.0	64.9	48.9
After harvesting					
Control	= No salt	6.8	1.6	1.1	0.4
Saline	($NaCl + CaCl_2 + MgCl_2$)				
(1)120 $\mathrm{mmol_c\,l^{-1}}$	= 40 + 40 + 40	6.3	7.5	2.7	2.7
(2)150 $\mathrm{mmol_c\,l^{-1}}$	= 50 + 50 + 50	6.2	9.7	2.2	2.0
(3)180 $\mathrm{mmol_c\,l^{-1}}$	= 60 + 60 + 60	6.2	12.0	2.5	2.0
Sodic	($NaHCO_3$)				
(1)120 $\mathrm{mmol_c\,l^{-1}}$	=120	8.2	2.0	20.7	23.0
(2)150 $\mathrm{mmol_c\,l^{-1}}$	= 150	8.7	3.0	33.6	32.9
(3)180 $\mathrm{mmol_c\,l^{-1}}$	= 180	8.9	4.5	51.3	43.1

Total Carbon (%) = 3.8
Total N (%) = 0.28

Soil texture

Sand total = 46.8 %
Coarse 2000 to 630 μ m = 9.0 %
Medium 630 to 200 μ m = 17.7 %
Fine 200 to 63 μ m = 20.0 %
Silt = 34.1 %
Clay = 19.2 %
Class Clay loam soil (UK classification)

All soil chemical properties changed during the course of the experiment. Soil pH showed a slight increase while EC_e, ESP and SAR decreased between sowing and harvest. These decreases were greater in the saline than in the sodic soil.

10.4.2 Results of Experiment 10

10.4.2.1 Effects of saline and sodic soil treatments on seedling emergence of $R112^+$ and $R21^-$ genotypes

There were significant differences between salt treatments in the percentage of emerged seedlings (Fig 10.1a and Table 10.1). In the control soil treatment about 85% of the seedlings emerged within 10 days, but in the saline and sodic soil treatments the emergence was still below 40% and 65% respectively. Thus the effect of sodicity was less severe than that of salinity. Although the seedling emergence percentage in sodic soil treatments was significantly lower than the control at 10 days after sowing, the difference was not significant at 15 and 20 days after sowing. Salinity decreased and delayed seedling emergence. Seedling emergence percentage decreased with increasing salinity. At medium (150 $mmol_c$ l^{-1}) and high salinity (180 $mmol_c$ l^{-1}) treatments, the mean final seedling emergence % was significantly lower compared to the control and other saline and sodic soil treatments. The average final emergence percentage over all treatments showed no significant difference between genotypes (Fig 10.1b, and Table 10.1).

Differences between genotypes were significant at low (120 $mmol_c$ l^{-1}) soil salinity and high soil sodicity treatments (Table 10.1). Genotype $R21^-$ had significantly higher emergence at low soil salinity. $R112^+$ had higher emergence than $R21^-$ at both high salinity and high sodicity, although the difference was significant under high sodicity only (Figures 10.1c and d).

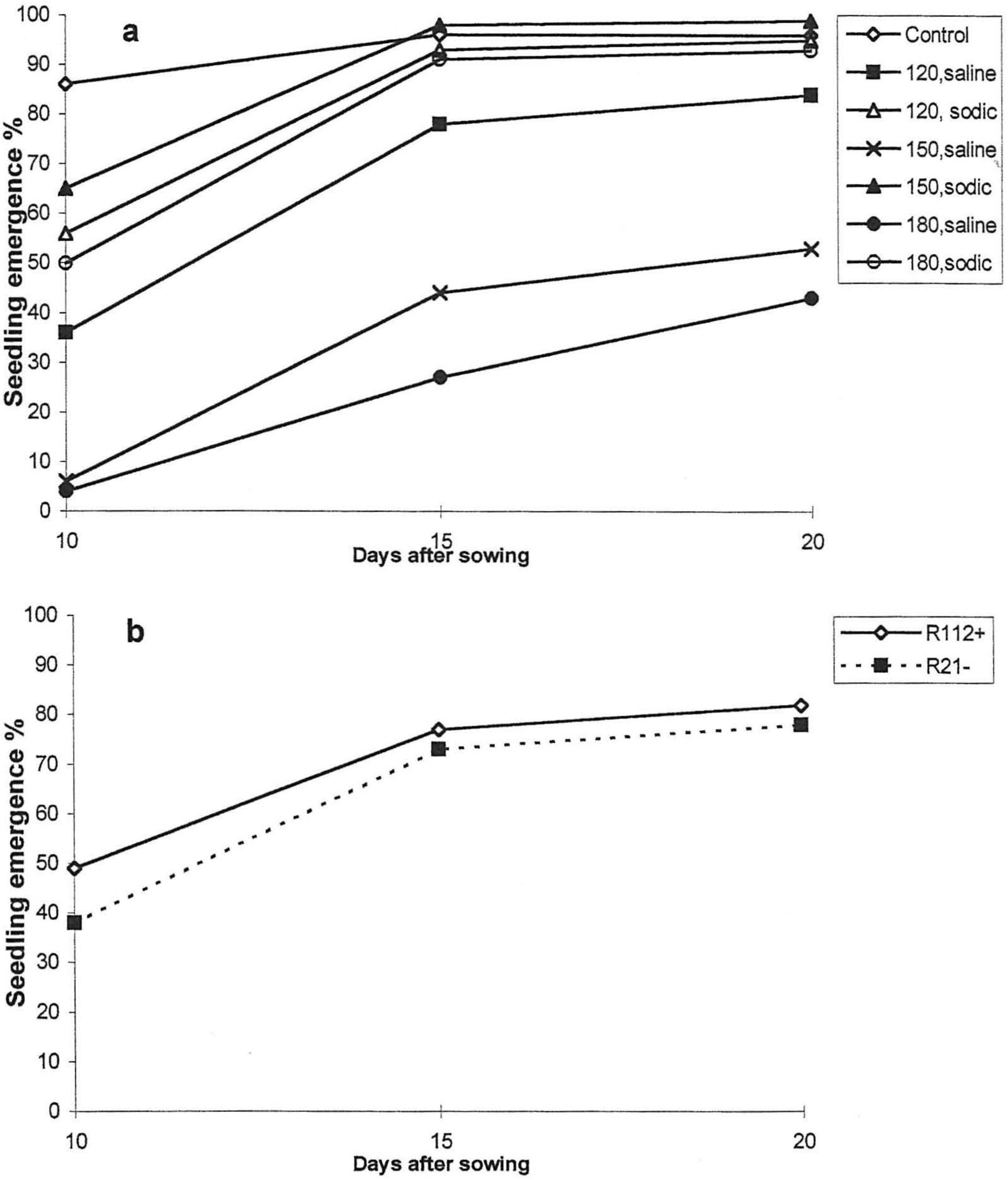


Figure 10.1 Effects of (a) different salt treatments (mmol$_c$ l^{-1}) and (b) genotypes on seedling emergence (%)

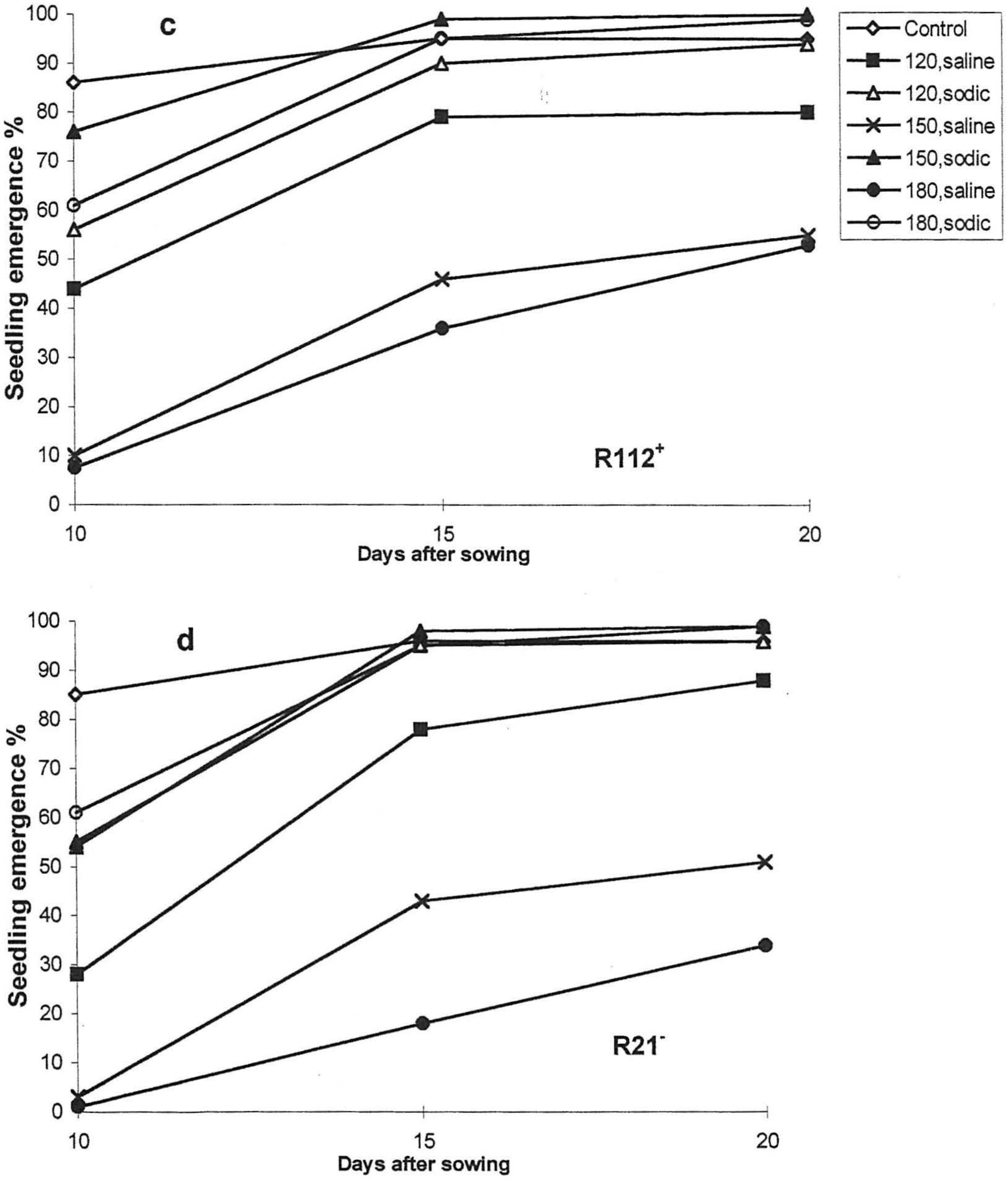


Figure 10.1 Effects of different salt treatments (mmol$_c$ l^{-1}) on seedling emergence % of (c) R112$^+$ and (d) R21$^-$ (durum wheat genotypes)

Table 10.1. Effect of saline and sodic salts on the seedling emergence (%) of two durum wheat genotypes

	Genotypes		
Soil treatment	R112$^+$	R21$^-$	Means
Seedling emergence % (20 DAS)			
Control	95	96	95.6
120 mmol$_c$ l^{-1}Saline	80	88	83.7
120 mmol$_c$ l^{-1}Sodic	94	96	95.0
150 mmol$_c$ l^{-1}Saline	55	51	53.1
150 mmol$_c$ l^{-1}Sodic	100	99	99.4
180 mmol$_c$ l^{-1}Saline	53	34	43.1
180 mmol$_c$ l^{-1}Sodic	99	86	92.5
Means	82.1	78.5	
Transformed data [arcsine (%/100)]			
Control	1.35	1.43	1.392
120 mmol$_c$ l^{-1}Saline	0.98	1.24	1.111
120 mmol$_c$ l^{-1}Sodic	1.26	1.37	1.322
150 mmol$_c$ l^{-1}Saline	0.59	0.56	0.578
150 mmol$_c$ l^{-1}Sodic	1.57	1.49	1.531
180 mmol$_c$ l^{-1}Saline	0.55	0.34	0.450
180 mmol$_c$ l^{-1}Sodic	1.49	1.05	1.272
Means	1.115	1.073	

Standard error and least significant difference for comparison:

	Between salt treatments	Between genotypes	Between genotypes within one salt treatment	Between salt treatments for the same or different genotypes
Seedling emergence (arcsine values)				
S. E. D.	0.149	0.047	0.123	0.173
L. S. D.	0.315* * *	N. S	0.256*	0.361*

10.4.3 Results of Experiment 11.

Effects of soil salinity and sodicity on seedling emergence, ion uptake, growth and yield of R112$^+$ and R23$^-$ genotypes

10.4.3.1 Effects on seedling emergence (%)

Similarly in this experiment there were significant differences between the salt treatments in the percentage of seedlings emerged (Figure 10.2a, and Table 10.2). High salinity and high sodicity significantly decreased mean final emergence percentage. The effect of salinity was greater than that of sodic soil. The differences between genotypes and the interaction were not statistically significant (Table 10.2 and Figures 10.2b and c).

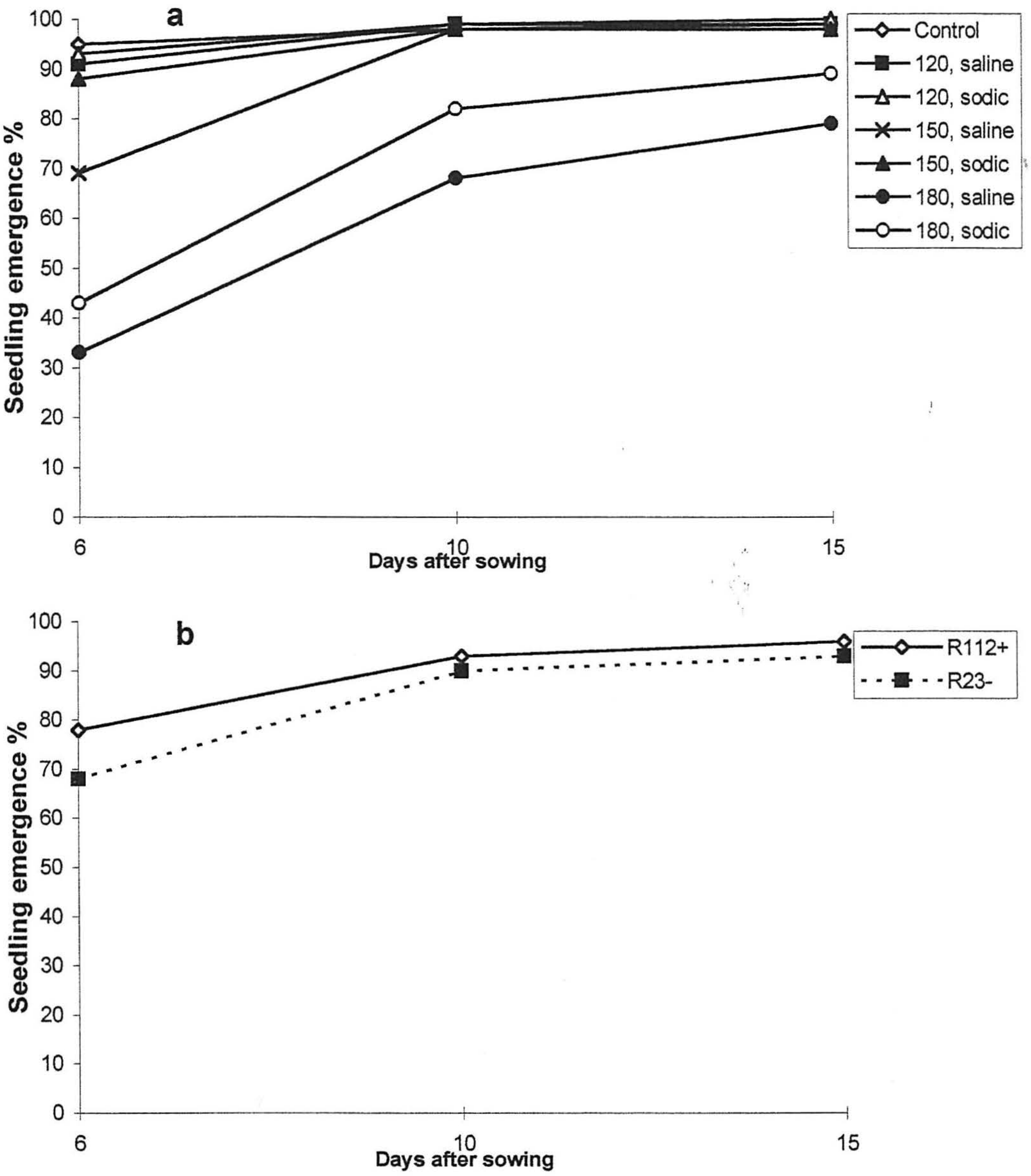


Figure 10.2 Effects of (a) different salt treatments (mmol$_c$ l^{-1}) and (b) genotypes on seedling emergence (%)

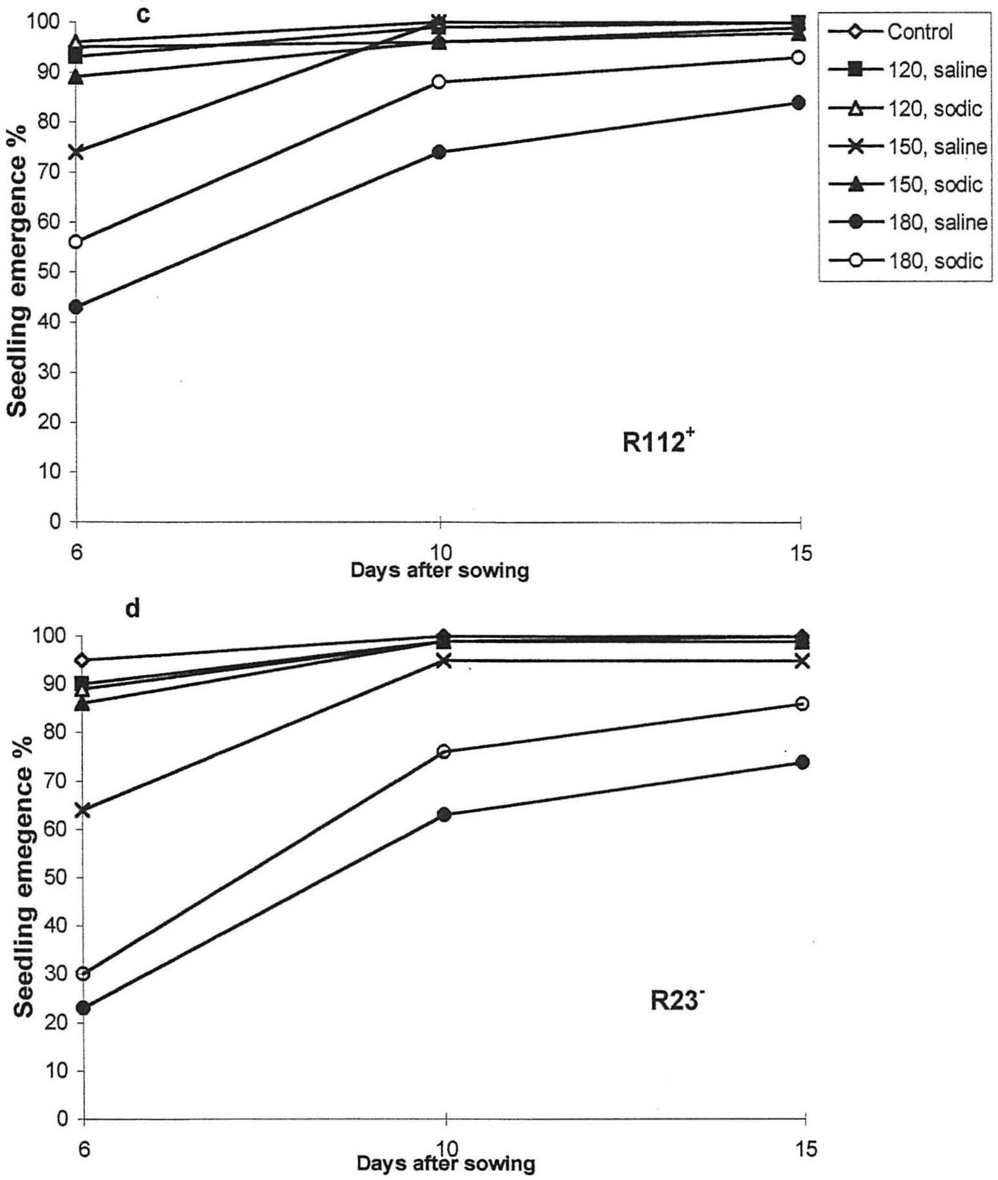


Figure 10.2. Effects of different salt treatments (mmol$_c$ l^{-1}) on seedling emergence (%) of (c) R112$^+$ and (d) R23$^-$ (durum wheat genotypes)

Table 10.2. Effect of saline and sodic soil treatments on the seedling emergence % of two durum wheat genotypes

Soil treatment	Genotypes		Means
	$R112^+$	$R23^-$	
Seedling emergence % (15 DAS)			
Control	99	100	99.4
120 mmol$_c$ l^{-1}Saline	100	99	99.4
120 mmol$_c$ l^{-1}Sodic	100	100	100.0
150 mmol$_c$l^{-1}Saline	100	95	97.5
150 mmol$_c$ l^{-1}Sodic	98	99	98.1
180 mmol$_c$ l^{-1}Saline	84	74	78.7
180 mmol$_c$ l^{-1}Sodic	93	86	89.4
Means	96.1	93.2	
Transformed data [arcsine (%/100)]			
Control	1.49	1.57	1.531
120 mmol$_c$ l^{-1}Saline	1.57	1.49	1.531
120 mmol$_c$ l^{-1}Sodic	1.57	1.57	1.570
150 mmol$_c$ l^{-1}Saline	1.57	1.40	1.490
150 mmol$_c$ l^{-1}Sodic	1.41	1.49	1.451
180 mmol$_c$l^{-1}Saline	1.07	0.93	0.998
180 mmol$_c$ l^{-1}Sodic	1.31	1.05	1.182
Means	1.427	1.359	

Standard error and least significant difference for comparison:

	Between salt treatments	Between genotypes	Between genotypes within one salt treatment	Between salt treatments for the same or different genotypes
Seedling emergence (arcsine values)				
S. E. D.	0.136	0.039	0.105	0.155
L. S. D.	0.332* *	N. S.	N. S.	N. S.

10.4.3.2 Effects on survival %

The effects of saline and sodic soil treatments on the % of plants that survived with ears at maturity are shown in Table 10.2.1. The mean survival percentage was significantly different between salt treatments. The effect of saline soil treatments was greater than that of sodic soil treatments. The treatment of soil with low, medium and high salinity levels significantly decreased survival, but the treatment of soil with sodicity had a significant adverse effect only at the high level. The average survival % of both genotypes over all treatments showed that survival % of $R112^+$ was significantly higher than that of $R23^-$. The interaction between genotypes and salt treatments was not significant.

Table 10.2.1. Effect of saline and sodic soil treatments on the survival % of two durum wheat genotypes with ears at maturity

	Genotypes		
Soil treatment	R112$^+$	R23$^-$	Means
Survival %			
Control	100	100	100.0
120 $\text{mmol}_c\ l^{-1}$ Saline	95	78	86.2
120 $\text{mmol}_c\ l^{-1}$ Sodic	100	100	100.0
150 $\text{mmol}_c\ l^{-1}$ Saline	85	70	77.5
150 $\text{mmol}_c\ l^{-1}$ Sodic	100	80	90.0
180 $\text{mmol}_c\ l^{-1}$ Saline	65	53	58.7
180 $\text{mmol}_c\ l^{-1}$ Sodic	100	90	95.0
Means	92.1	81.4	
Transformed data [arcsine (%/100)]			
Control	1.57	1.57	1.57
120 $\text{mmol}_c\ l^{-1}$ Saline	1.41	0.97	1.19
120 $\text{mmol}_c\ l^{-1}$ Sodic	1.57	1.57	1.57
150 $\text{mmol}_c\ l^{-1}$ Saline	1.09	0.78	0.94
150 $\text{mmol}_c\ l^{-1}$ Sodic	1.57	1.02	1.29
180 $\text{mmol}_c\ l^{-1}$ Saline	0.81	0.60	0.70
180 $\text{mmol}_c\ l^{-1}$ Sodic	1.57	1.25	1.41
Means	1.37	1.11	

Standard error and least significant difference for comparison:

	Between salt treatments	Between genotypes	Between genotypes within one salt treatment	Between salt treatments for the same or different genotypes
Survival % (arcsine values)				
S. E. D.	0.163	0.060	0.160	0.257
L. S. D.	0.343* * *	0.127* * *	N. S	N. S

10.4.3.3 Effects on ion concentrations

Tables 10.2.2 and 10.2.3 show the ion concentrations in sap extracted from the expanded flag leaves of both genotypes grown in the 150 $\text{mmol}_c\ l^{-1}$ saline and sodic soil treatments. Salinity significantly increased the concentration of Na^+, Ca^{2+} and Cl^- but decreased the K^+/Na^+ ratio. Although it was not significant, the concentration of Mg^{2+} was higher and of K^+ was lower in the saline soil treatment compared to the control . In the sodic soil treatment plants had significantly higher Na^+ and significantly lower K^+, Ca^{2+} and K^+/Na^+ ratio and non significantly higher Mg^{2+} than other soil treatments. The concentration of Cl^- was significantly higher in the saline soil treatment than in the control and sodic soil treatments. With the exception of K^+/Na^+ ratio all interactions were significant, showing that the effects of salt-treatments on ion concentrations varied with genotype. K^+/Na^+ ratio consistently higher in R112$^+$ than R23$^-$, indicating the presence of the Kna1 discriminating gene. In R23$^-$ genotype the mean Na^+, Ca^{2+} and Cl^- concentrations were significantly higher but K^+/Na^+ ratio was significantly lower than in R112$^+$. In the control soil treatment, there were no significant differences between the genotypes in the accumulation of ions. In the saline soil treatment, R23$^-$ accumulated significantly higher Na^+, Ca^{2+} and Cl^- than R112$^+$.

Table 10.2.2. Effect of saline and sodic soil treatments on the concentrations of Na^+ and K^+ and K^+/Na^+ ratio in the sap of fully expanded flag leaf of two durum wheat genotypes

	Genotypes		
Soil treatment	R112$^+$	R23$^-$	Means
Na^+ mol m^{-3}			
Control	6	7	6.0
150 mmol$_c$ l^{-1}Saline	14	88	50.7
150 mmol$_c$ l^{-1}Sodic	37	317	176.7
Means	18.8	136.8	
K^+ mol m^{-3}			
Control	104	120	111.6
150 mmol$_c$ l^{-1}Saline	103	105	103.7
150 mmol$_c$ l^{-1}Sodic	85	46	65.7
Means	90.0	97.3	
K^+/Na^+			
Control	19.2	18.8	19.0
150 mmol$_c$ l^{-1}Saline	7.4	1.2	4.3
150 mmol$_c$ l^{-1}Sodic	2.3	0.1	1.2
Means	9.6	6.7	

Standard error and least significant difference for comparison:

	Between salt treatments	Between genotypes	Between genotypes within one salt treatment	Between salt treatments for the same or different genotypes
Na^+ mol m^{-3}				
S. E. D.	3.57	3.49	6.04	5.56
L. S. D.	8.73* * *	7.88* * *	13.66* * *	12.59* * *
K^+ mol m^{-3}				
S. E. D.	6.37	7.33	12.69	11.01
L. S. D.	15.60* *	N. S.	28.70*	24.90*
K^+/Na^+				
S. E. D.	0.50	1.07	1.86	4.39
L. S. D.	1.34* * *	2.42*	N. S	N. S

Table 10.2.3. Effect of saline and sodic soil treatments on the concentrations of Ca^{2+}, Mg^{2+} and Cl^{-} in the sap of fully expanded flag leaf of two durum wheat genotypes

	Genotypes		
Soil treatment	R112^{+}	R23^{-}	Means
Ca^{2+} mol m^{-3}			
Control	28	33	30.5
150 mmol$_c$ l^{-1}Saline	48	116	82.0
150 mmol$_c$ l^{-1}Sodic	6	6	6.0
Means	27.4	51.8	
Mg^{2+} mol m^{-3}			
Control	35	27	31.1
150 mmol$_c$ l^{-1}Saline	50	67	58.1
150 mmol$_c$ l^{-1}Sodic	27	11	18.9
Means	37.3	34.7	
Cl^{-} mol m^{-3}			
Control	143	123	132.5
150 mmol$_c$ l^{-1}Saline	255	340	297.5
150 mmol$_c$ l^{-1}Sodic	117	171	143.6
Means	171.3	211.1	

Standard error and least significant difference for comparison:

	Between salt treatments	Between genotypes	Between genotypes within one salt treatment	Between salt treatments for the same or different genotypes
Ca^{2+} mol m^{-3}				
S. E. D.	1.76	1.59	2.75	2.62
L. S. D.	4.31 * * *	3.60* * *	6.23* * *	5.94* * *
Mg^{2+} mol m^{-3}				
S. E. D.	6.49	4.36	7.55	8.40
L. S. D.	N. S	N. S	17.07*	19.01*
Cl^{-} mol m^{-3}				
S. E. D.	23.4	12.6	21.7	22.9
L. S. D.	57.34* *	28.0*	49.2*	51.8*

There were no significant differences between the genotypes in K^{+}, Mg^{2+} and K^{+}/Na^{+} ratio in the saline soil treatment. In the sodic soil treatment, R23^{-} accumulated significantly higher Na^{+} and Cl^{-}, but it had significantly lower K^{+} and non significantly lower K^{+}/Na^{+} ratio compared to the R112^{+} genotype.

In the saline soil treatment, R112^{+} had significantly higher Ca^{2+} and Cl^{-}, than the control. There were no significant differences between the plants of R112^{+} grown in the saline and control soil treatments in Na^{+}, K^{+}, Mg^{2+} and K^{+}/Na^{+} ratio. Under sodic soil conditions the plants of R112^{+} had significantly higher Na^{+}, lower Ca^{2+} and non significantly lower K^+, K^+/Na^+ ratio and Mg^{2+} than the control. The Cl^- concentration in R112$^+$ plants in the sodic soil treatment was non significantly higher than in the control but was significantly lower than in the saline soil treatment.

In the saline treatment, R23$^-$ had a significantly higher concentration of Na^+, Ca^{2+}, Mg^{2+} and Cl^- than the control. However, there were no significant differences between these treatments in K^+/Na^+ ratio and K^+ accumulated by R23$^-$. Similarly, the Na^+ concentration was significantly higher and the K^+, Ca^{2+}, Mg^{2+} and K^+/Na^+ ratio were significantly lower in the sodic than in the control and saline soil treatments. Cl^- showed a similar trend as in R112$^+$ being lower in the sodic than saline, but higher than in the control soil treatments. Over all in both saline and sodic soil conditions, R23$^-$ showed a high concentration of Na^+ and Cl^-, and lower K^+ and K^+/Na^+ ratio than R112$^+$.

10.4.3.4 Effects on growth and development

Saline and sodic soil treatments had a significant effect on plant height (Table 10.2.4). Plant height decreased with increasing salinity and sodicity. The effect of salinity on plant height was lower than that of sodicity. The differences between genotypes over all soil treatments showed that the plants of R112$^+$ were taller than R23$^-$. Within each salt treatment the plants of R112$^+$ were taller than R23$^-$. Both saline and sodic soil treatments had no significant effect on the height of R112$^+$, but the height of plants of R23$^-$ decreased with increasing sodicity and salinity.

There was a significant difference between the salt treatments in the number of fully expanded leaves on the main stem (Table 10.2.4). The number of fully expanded leaves on the main stem was significantly lower in the medium and high saline and sodic soil treatments than in the control and low saline and sodic soil treatments. There was no significant difference between the genotypes. The interaction of genotypes with saline or sodic soil treatments was not statistically significant. There was a significant difference between the salt treatments in the number of tillers produced by plants at flag leaf stage (Table 10.2.4). Tiller production decreased with increasing salinity. Although it was lower than the control soil treatment, the number of tillers increased with increasing sodicity. R112$^+$ produced significantly more tillers than R23$^-$ in each of the saline and sodic soil treatments.

Table 10.2.4. Effect of saline and sodic soil treatments on height, number of fully expanded leaves on the main stem and number of tillers /plant of two durum wheat genotypes

Soil treatment	Genotypes R112$^+$	R23$^-$	Means
Height (cm) at maturity			
Control	108	99	103.4
120 mmol$_c$ l^{-1} Saline	109	85	96.8
120 mmol$_c$ l^{-1} Sodic	108	81	94.3
150 mmol$_c$ l^{-1} Saline	107	69	88.1
150 mmol$_c$ l^{-1} Sodic	100	66	83.2
180 mmol$_c$ l^{-1} Saline	102	68	85.1
180 mmol$_c$ l^{-1} Sodic	100	62	80.8
Means	104.8	75.6	
No. of main stem fully expanded leaves/plant (58 DAS)			
Control	6	7	6.5
120 mmol$_c$ l^{-1} Saline	6	6	6.4
120 mmol$_c$ l^{-1} Sodic	6	6	6.3
150 mmol$_c$ l^{-1} Saline	6	6	5.9
150 mmol$_c$ l^{-1} Sodic	6	6	6.1
180 mmol$_c$ l^{-1} Saline	5	5	4.9
180 mmol$_c$ l^{-1} Sodic	6	6	6.1
Means	5.9	6.1	
No. of tillers/plant (58 DAS)			
Control	2.5	1.3	1.85
120 mmol$_c$ l^{-1} Saline	1.2	0.3	0.74
120 mmol$_c$ l^{-1} Sodic	2.0	0.3	1.15
150 mmol$_c$ l^{-1} Saline	0.8	0.1	0.46
150 mmol$_c$ l^{-1} Sodic	2.4	0.6	1.51
180 mmol$_c$ l^{-1} Saline	0.6	0.0	0.33
180 mmol$_c$ l^{-1} Sodic	3.0	0.7	1.66
Means	1.73	0.46	

Standard error and least significant difference for comparison:

	Between salt treatments	Between genotypes	Between genotypes within one salt treatment	Between salt treatments for the same or different genotypes
Height				
S. E. D.	4.5	1.8	4.8	5.6
L. S. D.	9.4* *	3.8* * *	10.1* *	12.4* *
No. leaves/plant				
S. E. D.	0.11	0.04	0.31	0.17
L. S. D.	0.28* *	N. S	N. S	N. S
No. tillers/plant				
S. E. D.	0.234	0.40	0.24	0.29
L. S. D.	0.49* * *	0.84* * *	0.50* *	0.60* *

10.4.3.5 Effects on yield and yield components

Tables 10.2.5, 10.2.5a and b show the yield and yield components of both genotypes grown under different saline and sodic soil treatments. Averaged over all genotypes the grain weight/plant decreased as salt concentration increased. The effects of sodicity were greater than the effects of salinity, and the effects of both treatments were greater in $R23^-$ than in $R112^+$. At the highest levels tested, grain weight/plant was significantly decreased by salinity and sodicity in $R23^-$, but by sodicity only in $R112^+$.

The decreases in grain weight per plant were due mainly to decrease in the number of grains per plant and 1000 grain weight. For both these components the effects of sodicity were greater than those of salinity and were greater in $R23^-$ than $R112^+$. The number of ears/plant was relatively unaffected. Though there was no significant difference between the salt treatments, the straw weight/plant was generally lower in the saline soil treatments than in the sodic soil treatments, and it was significantly lower in $R23^-$ than in $R112^+$.

As soil salinity and sodicity decreased the emergence and survival of plants, as well as grain weight/plant, they had large effects on grain and straw weight/m^2. The decrease in grain weight/m^2 was greater in the sodic than in the saline soil treatments, but the decrease in straw weight/m^2 was greater in saline soil treatments than in sodic soil treatments. The straw weight/m^2 in $R23^-$ was greatly decreased by both salinity and sodicity, but in $R112^+$ it was decreased only by salinity. Genotype $R112^+$ had significantly higher grain and straw weight/m^2 than $R23^-$ genotype.

The effect of increasing salt concentration was also to decrease the harvest index. The decrease in harvest index was significant in all sodic soil treatments, whereas in the saline soil treatments the decrease was significant only in high saline soil treatment. The harvest index in $R112^+$ was significantly affected by high sodicity, but not by other salt treatments, but in $R23^-$ compared to the control soil treatment, harvest index was lower in almost all salt treatments.

Table 10.2.5. Effect of saline and sodic soil treatments on number of ears, number of grains per plant and 1000 grain weight (g) of two durum wheat genotypes

	Genotypes		
Soil treatment	R112$^+$	R23$^-$	Means
No. of ears/plant			
Control	1.7	1.1	1.40
120 mmol$_c$ l^{-1} Saline	1.3	1.0	1.15
120 mmol$_c$ l^{-1} Sodic	1.6	1.0	1.36
150 mmol$_c$ l^{-1} Saline	1.2	1.1	1.15
150 mmol$_c$ l $^{-1}$ Sodic	1.6	1.0	1.28
180 mmol$_c$ l^{-1} Saline	1.2	1.1	1.12
180 mmol$_c$ l^{-1} Sodic	1.2	1.0	1.07
Means	1.39	1.05	
No. of grains/plant			
Control	13	15	13.8
120 mmol$_c$ l^{-1} Saline	18	11	14.5
120 mmol$_c$ l^{-1} Sodic	12	5	8.6
150 mmol$_c$ l^{-1} Saline	19	8	13.7
150 mmol$_c$ l $^{-1}$ Sodic	11	3	6.8
180 mmol$_c$ l^{-1} Saline	19	9	14.3
180 mmol$_c$ l^{-1} Sodic	4	2	2.9
Means	13.8	7.5	
1000 grain weight (g)			
Control	47	44	45.1
120 mmol$_c$ l^{-1} Saline	43	37	40.4
120 mmol$_c$ l^{-1} Sodic	45	35	39.8
150 mmol$_c$ l^{-1} Saline	38	20	29.0
150 mmol$_c$ l^{-1} Sodic	39	31	34.7
180 mmol$_c$ l^{-1} Saline	37	6	21.6
180 mmol$_c$ l^{-1} Sodic	34	21	27.5
Means	40.4	27.7	

Standard error and least significant difference for comparison:

	Between salt treatments	Between genotypes	Between genotypes within one salt treatment	Between salt treatments for the same or different genotypes
No. of ears/plant				
S. E. D.	0.111	0.054	0.143	0.151
L. S. D.	N. S	0.113* * *	0.301*	0.316*
No. of grains/plant				
S. E. D.	2.49	1.31	3.47	3.49
L. S. D.	5.2* *	2.7* * *	N. S	N. S
1000 grain weight				
S. E. D.	3.4	1.4	3.7	4.3
L. S. D.	7.2* * *	2.9* * *	7.8 * * *	9.0 * * *

Table 10.2.5a. Effect of saline and sodic soil treatments on harvest index, straw and grain weight per plant of two durum wheat genotypes

	Genotypes		
Soil treatment	R112$^+$	R23$^-$	Means
Straw weight (mg)/plant			
Control	2870	1360	2110
120 mmol$_c$ l^{-1}Saline	2780	1195	1988
120 mmol$_c$ l^{-1}Sodic	3150	1107	2120
150 mmol$_c$ l^{-1}Saline	3100	708	1904
150 mmol$_c$ l^{-1}Sodic	3500	920	2220
180 mmol$_c$ l^{-1}Saline	3220	967	2098
180 mmol$_c$ l^{-1}Sodic	3100	321	1715
Means	3109	940	
Grain weight (mg)/plant			
Control	609	648	628.6
120 mmol$_c$ l^{-1}Saline	746	427	586.9
120 mmol$_c$ l^{-1}Sodic	586	177	381.1
150 mmol$_c$ l^{-1}Saline	717	187	452.2
150 mmol$_c$ l^{-1}Sodic	447	95	271.1
180 mmol$_c$ l^{-1}Saline	693	54	373.5
180 mmol$_c$ l^{-1}Sodic	140	32	86.1
Means	562.6	231.6	
Harvest Index (%)			
Control	18	33	25.2
120 mmol$_c$ l^{-1}Saline	21	27	23.8
120 mmol$_c$ l^{-1}Sodic	15	13	14.0
150 mmol$_c$ l^{-1}Saline	20	22	21.0
150 mmol$_c$ l^{-1}Sodic	10	9	9.6
180 mmol$_c$ l^{-1}Saline	18	5	11.6
180 mmol$_c$ l^{-1}Sodic	4	9	6.5
Means	15.1	16.8	

Standard error and least significant difference for comparison:

	Between salt treatments	Between genotypes	Between genotypes within one salt treatment	Between salt treatments for the same or different genotypes
Straw weight (mg)/plant				
S. E. D.	195.0	377.0	330.8	377.0
L. S. D.	N. S	785.9 * * *	N. S	N. S
Grain weight (mg)/plant				
S. E. D.	118.7	52.6	139.2	154.3
L. S. D.	246.9* *	109.4* * *	289.7*	320.8*
Harvest Index (%)				
S. E. D.	4.2	1.6	4.3	5.2
L. S. D.	8.8* *	N. S	8.9* *	10.7* *

Table 10.2.5b. Effect of saline and sodic soil treatments on grain and straw yield /m^2 of two durum wheat genotypes

Soil treatment	Genotypes		Means
	R112^{+}	R23^{-}	
Grain weight (g)/m^2			
Control	380	404	392.1
120 mmol$_c$ l^{1}Saline	441	198	319.8
120 mmol$_c$ l^{1}Sodic	366	110	238.2
150 mmol$_c$ l^{1}Saline	369	79	224.4
150 mmol$_c$ l^{1}Sodic	294	45	169.4
180 mmol$_c$ l^{1}Saline	271	17	143.9
180 mmol$_c$ l^{1}Sodic	88	18	52.6
Means	315.6	124.5	
Straw weight (g)/m^2			
Control	1792	849	1320.6
120 mmol$_c$ l^{1}Saline	1639	551	1094.8
120 mmol$_c$ l^{1}Sodic	1969	692	1330.5
150 mmol$_c$ l^{1}Saline	1552	274	913.3
150 mmol$_c$ l^{1}Sodic	2197	416	1306.5
180 mmol$_c$ l^{1}Saline	1301	300	800.8
180 mmol$_c$ l^{1}Sodic	1944	177	1060.3
Means	1770.8	465.5	

Standard error and least significant difference for comparison:

	Between salt treatments	Between genotypes	Between genotypes within one salt treatment	Between salt treatments for the same or different genotypes
Grain weight (g)/m^2				
S. E. D.	67.8	32.2	52.6	90.7
L. S. D.	142.4* *	67.0* * *	N. S	N. S
Straw weight (g)/m^2				
S. E. D.	136.8	67.3	178.1	185.9
L. S. D.	287.4* *	140.0* * *	370.4*	386.7*

10.5 Discussion

10.5.1 Soil

Following treatments of the soil with salts large increases in EC$_e$ values occurred only in the saline soil treatments. In the sodic soil treatments, there were larger increases than in the saline soil treatments in pH, SAR, and ESP (Table 10). The increases in EC$_e$ in the saline soil treatments were related to the addition of the salt mixture, and the increases in SAR, pH and ESP values in the sodic soil treatments were associated with the addition of an alkaline salt ($NaHCO_3$). According to Landon (1984), on the basis of EC_e values, the soils in the saline treatments are classified as: salt free (control soil), moderately saline (120 $mmol_c\ l^{-1}$) and strongly saline (150 and 180 $mmol_c\ l^{-1}$) soils. On the basis of SAR and ESP, the sodic soil treatments are classified as: moderately (120 and 150 $mmol_c\ l^{-1}$) and strongly sodic (180 $mmol_c\ l^{-1}$) soils. These soils were medium in N contents (<0.5 %) (Landon, 1984). The sodic soil treatment at 120 $mmol_c\ l^{-1}$ $NaHCO_3$ had a lower pH value than the very often considered threshold value (> 8.5) for sodic soils. This was possibly because pH was measured using a lower dilution (1:2.5) than that generally used by other workers (1:5, soil water extract ratio).

As in other experiments reported in this thesis, there were large changes in the values of EC_e, SAR, ESP and pH between sowing and harvest. As it is already mentioned in the earlier experiments (Chapter 8) that these changes were possibly due to leaching caused by applications of tap water for the purpose of irrigation. Leaching might cause the decreases in SAR and ESP. Some other factors (Rowell, 1994) can also decrease SAR and ESP with time i.e. adsorption of Ca^{2+}, exchange of Na^+ with H^+ from the water applied, release of clay components e.g. Mg^{2+} and other cations, which can be exchanged with adsorbed Na^+.

For example: $\mathbf{Clay}^{2-}\ Na_2 + 2H_2O = \mathbf{Clay}^{2-}\ H_2 + 2Na^+ + 2\ OH^-$

$$\Downarrow$$

$$\mathbf{Clay}^{2-}\ Mg^{2+}$$

10.5.2 Plants

10.5.2.1 Effects of saline and sodic soil treatments

The effects of salinity on emergence and survival were greater than the effects of sodicity (Figures 10.1a, b, c, d, 10.2a, b, c and d, Tables 10.1, 10.2, 10.2.1 and 10.2.6a). Sodicity decreased emergence only at high ESP level in Experiment 11. This suggests that sodicity delayed emergence but salinity delayed as well as decreased the final emergence. These effects are also comparable with the results of Experiment 2 (Chapter 5), showing similar types of salinity and sodicity effects. These results indicate that high concentrations of soluble salts (salinity) decreased germination and hence emergence, but

Table 10.2.6a Summary table showing the % changes (decrease (-) or increase) over control for emergence, survival %, ion concentrations and yield of durum wheat

Parameter	Control	Saline soil treatment			Sodic soil treatments		
			$\text{mmol}_c\ l^{-1}$			$\text{mmol}_c\ l^{-1}$	
	Actual value	120	150	180	120	150	180
Emergence % (Exp. 10)	95.6	-12.4	-44.4	- 55.0	-0.6	3.9	- 3.2
Emergence % (Exp. 11)	99.4	0.0	-1.9	- 20.8	0.6	-1.3	-10.0
Survival %	100.0	-6.3	-22.5	-41.3	0.0	-10.0	- 5.0
Height	103.4	-13.8	-14.8	- 17.7	-8.8	19.5	-21.9
Grain yield /plant	628.6	-6.6	-28.1	40.6	-39.4	-56.9	-86.3
Na^+ mol m^{-3}	6.0		8.4			29.4	
K^+ mol m^{-3}	111.6		-7.7			-41.1	
K^+/Na^+	19.0		-77.0			-93.6	
Ca^{2+} mol m^{-3}	30.5		168.8			-80.3	
Mg^{2+} mol m^{-3}	31.1		86.8			-39.2	
Cl^- mol m^{-3}	132.5		124.5			8.4	

high pH and SAR did not. This suggests that the effects in saline treatments are osmotic or due to Cl^-, not due to high Na^+ concentrations, as ESP was higher in the sodic treatments. In Experiment (11) seedlings emerged faster than they emerged in the Experiment 10. That was possibly due to the different environmental conditions (Sections 10.3.2 and 10.3.3), because in the growth room temperature was higher than in the glasshose.

Salinity but not sodicity decreased plant survival. The decrease in survival was due to death and shortage of plants with ears at maturity and low emergence in saline soil treatments (Tables 10.2.1 and 10.2.6a).

Averaged over all genotypes, saline soil treatments had higher effect on the number of tillers and number of main stem leaves, and a smaller effect on shoot height (Table 10.2.6a) compared to the sodic soil treatments. That indicates that the adverse effects of salinity and /or sodicity on some characters were more or less similar but on other characters were largely different.

It is apparent from Tables 10.2.5, a, b and 10.2.6a, that grain and straw yields and yield components were adversely affected by salt-affected soil treatments, especially at high levels compared to the control soil treatment. The decreases in grain yield per plant in the saline soil treatments compared to the control were due to fewer ears and lighter grains. The larger decreases in grain yield per plant in the sodic soil treatments than the saline and control were due mainly to the fewer grains. Number of ears/plant and 1000 grain weight were generally higher under sodic conditions than saline conditions. The large decreases in grain number under sodic conditions suggest the greater effect of sodicity on pollination and fertilization. Similar effects of sodicity have also been observed in Experiment 7 (Chapter 8). The large decreases in 1000 grain weight under saline conditions suggest a greater effect of salinity on grain growth. The lower grain yield/m^2 in the saline soil treatments was due to both lower yield/plant and lower survival of plants to maturity. In the sodic soil treatments effects on survival were smaller, and the lower grain yield/m^2 was due mainly to lower yield/plant. Cereal crops can normally compensate for sub-optimal plant population by increased tillering, but this was not observed in this study, as salinity decreased tillering. Hence this suggests that one way to increase yield on salt-affected soils may be to increase seed rate. Due to the lower grain yield than straw yield, generally in all salt-affected soil treatments, but especially in sodic soil treatments, the harvest index values were very low compared to the control treatment values. This is partly because infertile secondary tillers were included in the straw weight, so that the harvest index value was lower than the value (50 %) more often found in wheat plants under normal conditions.

Ion analysis (Tables 10.2.2, 10.2.3 and 10.2.6a) of flag leaf sap (in 150 $mmol_c\ l^{-1}$ salt-affected soil treatments) provided evidence that the adverse effects of salinity were associated with higher concentrations of Na^+, Cl^-, Ca^{2+} and lower concentrations of K^+ and lower K^+/Na^+ ratio. The higher concentrations of Na, Ca^{2+}, Mg^{2+} and Cl^- ions in flag leaf sap were a reflection of the salt mixture ($NaCl$, $CaCl_2$ and $MgCl_2$) added into the soil while preparing the saline soil treatment. The adverse effects of sodicity on plants were associated with higher concentrations of Na^+ and lower concentrations of Ca^{2+}, and K^+ and lower K^+/Na^+ ratio compared to the control and saline soil treatments. Higher concentrations of leaf Na^+ in the sodic soil treatment were due to the preparation of the sodic soil using only $NaHCO_3$ salt. Similar trends for Na^+ and K^+ uptake in durum wheat under sodic soil conditions have also been recorded (Gorham *et al.*, 1997) and observed in the youngest fully expanded leaf sap of seedlings (Chapter 5, Section 5.5.3a,b and Section 5.6.3a,b).

Several factors could have contributed to the greater effect of sodicity on grain yield. These include poor soil structure, higher pH, ESP and higher leaf Na^+, lower K^+, and lower K^+/Na^+ ratio. However Cl^- concentration was generally similar in both the control and sodic treatments.

In the saline treatment concentrations of nutrient cations were greater (Ca^{2+} and Mg^{2+}) or similar (K^+) to the control. This suggests that yield decreased in these saline treatments was due to Na, Cl or osmotic effects or some other factors (e.g. P) not measured.

The flag leaf is the most important source of carbohydrate for the grain (Thorne, 1965). High Na^+ and Cl^- and low Ca^{2+}, Mg^{2+} and K^+ might be expected to have adverse effects on this source.

10.5.2.2 Genotypic effects

It is evident from the results (Tables 10.1, 10.2, 10.2.1 and 10.2.6b) that the effects of salinity on emergence, survival and grain wt/plant were greater on $R23^-$ than on $R112^+$. The greater effects of salinity on grain wt/plant were due to greater effects on grain number and 1000 grain weight. Salinity also had greater effects on growth of $R23^-$

Table 10.2.6b Summary table showing the percentage changes (decrease (-) or increase) over control in some important parameters of genotypes with and without Kna1 gene grown at different salinity and sodicity levels

Treatment	120 mmol$_c$ l^{-1}				150 mmol$_c$ l^{-1}				180 mmol$_c$ l^{-1}			
Soil	Saline		Sodic		Saline		Sodic		Saline		Sodic	
Gene	Kna1$^+$	Kna1$^-$	Kna1$^+$	Kna1$^-$	Kna1$^+$	Kna1$^-$	Kna1$^+$	Kna1$^-$	Kna1$^+$	Kna1$^-$	Kna1$^+$	Kna1$^-$
Emergence % I	-16.0	-8.3	-1.0	0.0	-44.1	-46.8	5.0	3.0	-49.5	-65.0	4.2	- 10.4
Emergence % II	1.0	- 1.0	1.0	0.0	1.0	- 5.0	- 1.0	- 1.0	- 15.0	- 26.0	- 6.0	- 14.0
Survival %	- 5.0	- 22.0	0.0	0.0	- 15.0	- 30.0	0.0	- 20.0	- 35.0	- 47.0	0.0	- 10.0
Grain yield/plant	22.0	- 34.1	- 3.8	-2.7	17.7	- 71.1	- 26.6	- 85.3	14.0	-91.7	- 77.0	- 95.0
Na^+ mol m^{-3}					2.3	12.5	6.2	19.6				
K^+ mol m^{-3}					- 9.6	- 12.5	- 18.3	- 61.7				
K^+/Na^+ ratio					- 61.5	- 93.6	- 88.0	- 99.4				
Ca^{2+} mol m^{-3}					71.4	251.5	- 78.6	- 81.8				
Mg^{2+} mol m^{-3}					43.0	59.7	- 22.8	- 59.3				
Cl^- mol m^{-3}					78.3	176.4	18.2	39.0				

than R112$^+$ (Table 10.2.4). Greater effects of salinity on R23$^-$ were associated with higher flag leaf Na^+, Cl^- and lower K^+/Na^+ ratio. This indicates the absence of the Kna1 trait in R23$^-$.

The effects of sodicity on grain weight per plant were greater than the effects of salinity and also greater in R23$^-$ than R112$^+$.

The greater adverse effect of sodicity than salinity on R23$^-$ than on R112$^+$ were associated with higher concentrations of Na^+ and lower concentrations of K^+, Ca^{2+} and Mg^{2+} and lower K^+/Na^+ ratio (Table 10.2.2, Table 10.2.3 and Table 10.2.6b). Similar types of associations under sodic conditions in these genotypes have also been recorded by Gorham *et al.* (1997) and were noted in Experiments 3 and 4 (Chapter 5) reported in this thesis.

10.6 Conclusions

- Sodicity decreased grain yield more than salinity.
- The Kna1 gene, which allows plants to discriminate between K^+ and Na^+, is potentially useful under sodic as well as saline conditions.
- Grain yield per plant was low in this experiment possibly as this experiment was conducted under conditions that were sub-optimal for wheat. Hence there is a need for it to be repeated using more appropriate sowing dates and under field conditions.

CHAPTER 11

General discussion

CHAPTER 11

General discussion

The first aim of this chapter is to highlight the subject areas that were identified at the start of the research programme and to underscore several other areas which became apparent as the study progressed. A second important aim of this chapter is to suggest possible subjects for future research.

The importance of wheat as a food crop and the problems caused by salt-affected soils in Pakistan are not discussed in this chapter, which does not mean that they are considered unimportant, but they have already been discussed in Chapters 1 and 2 (Section 2.2) of this thesis.

11.1 Do salinity and sodicity have similar effects on wheat ?

The effects of sodicity were generally greater than salinity on almost all characteristics except seedling emergence. Salinity delayed and decreased seedling emergence but sodicity generally delayed rather than decreased emergence. This trend was generally consistent in almost all experiments (experiments 2, 10 and 11). Salinity also had a larger effect than sodicity on survival of plants with ears at maturity (experiments 10 and 11).

Shoot dry weight, shoot height (experiments 2 and 7), root length (experiment 2) and grain yield (experiment 7) were much lower under sodic conditions than saline. However this trend was not consistent in all experiments for all characteristics. In experiments 10 and 11, the effects of salinity were greater than sodicity on shoot dry weight, number of tillers and ears, whereas for other characteristics (shoot height and grain yield) the effects of sodicity were greater than salinity. In saline soil conditions possibly the effects were due to the osmotic effect of soluble salts and Cl^- toxicity, and in sodic soils the effects were most likely related with both poor physical conditions and Na^+ because the concentration of Na^+ in plants was higher in sodic soils (experiments 7, 10 and 11) than saline soils. In soils considered to be highly saline and highly sodic (experiments 10 and 11), although it was very low at high sodicity, harvest index was generally lower in both saline and sodic conditions. The effects of salinity on 1000 grain weight was greater than sodicity, but the plants grown at high sodicity had empty ears so that either they had no (experiment 7) or fewer (experiments 10 and 11) grains compared to high salinity. This suggests that although, sodicity is worse than salinity, both stresses are responsible for low wheat yield at high levels.

11.2 Are varieties resistant or sensitive to salinity in hydroponic culture also resistant or sensitive to salinity in soil culture ?

The responses of varieties to salinity were not the same in the two (hydroponic and soil culture) saline culture systems (experiments 2, 4 and 7). For example Q-19 was very sensitive to hydroponic salinity (experiment 1) compared to other varieties tested. Although Q-19 had lower shoot dry weight, grain yield was not lower in Q-19 than Kharchia-65 in saline soil conditions (experiment 7). The reason could be differences in the medium where they grew and differences in types and amounts of salts. In hydroponic culture only NaCl was used but in soil culture an equal mixture of NaCl, $CaCl_2$ and $MgCl_2$ was used (Section 3.1.1). Another reason could be the growth conditions as the hydroponic culture experiment was conducted in a growth room whereas the soil culture experiment was conducted in a glasshouse with no control of light and temperature. This indicates that varieties that are resistant to salinity under hydroponic culture may not be resistant or sensitive to salinity under field conditions, and highlights the importance of field testing and experimentation. Similar types of differences between the two culture salinities have also been observed by Ahsan (1996).

11.3 Do varieties that perform well under saline conditions also perform well under sodic conditions ?

The results of experiments conducted to compare varieties under saline and sodic conditions provided evidence that, amongst the tetraploid wheats tested (Chapter 10), genotypes which were sensitive to salinity were also sensitive to sodicity and those which were tolerant to salinity also remained tolerant to sodicity. However this trend was not observed for all hexaploid wheat varieties. Some varieties such as PAK-81 were found to be sensitive to both salinity as well as sodicity, and others (TW-161) were more tolerant to salinity than sodicity (experiment 2). In experiment 7 (Chapter 8), two varieties (Kharchia-65 and Q-19) responded differentially to salinity but equally to sodicity. This may indicate that Kharchia-65 and Q-19 were different in terms of their response to osmotic effects, but they were similar in terms of their response to sodicity. Hexaploid wheat varieties (Kharchia-65) and tetraploid wheat genotypes ($R112^+$ and $R173^+$) tolerant to salinity and or sodicity at seedling stage also remained tolerant up to maturity (Chapters 5, 6 and 10).

Tolerance of both sodicity and salinity was generally associated with low Na^+ and Cl^- and high K^+ uptake and high K^+/Na^+ ratio in some varieties (Chapters 5 and 10). However in some varieties this association was not observed (experiments 3 and 4). This suggests that there are other factors involved in tolerance of these soil conditions, for example, tolerance to poor physical conditions in sodic soil conditions.

Although it depends on the type of soil, level of sodicity or salinity and the stage of growth, generally the varieties and genotypes tested in this study can be grouped into the following categories:

- Tolerant to salinity = TW-161, NIAB-20.
- Tolerant to sodicity = Anmol
- Tolerant to salinity and sodicity = Kharchia-65, KTDH-19, SARC-1, Bakhtwar, $R112^+$ and $R173^+$.

However, although this study provided evidence for the above varieties and genotypes, further research is needed to test these varieties and genotypes again in saline and sodic soils under field conditions.

11.4 To what extent are high ESP and poor soil structure responsible for low wheat yield under sodic soil conditions ?

Soil sodicity had adverse effects on the survival % of plants with ears at maturity (Tables 6.2, 7.2, 9.2, and 10.2.1), seedling emergence (experiments 2, 3, 4, 10 and 11), growth of seedlings (experiments 2, 3 and 4) and mature plants (experiments 5, 6, 7, 8, 9, 10 and 11) and grain and straw yield and yield components (Chapters 6, 7, 8, 9 and 10). In most experiments the adverse effects of sodicity were generally small at low ESP and greater at high ESP (Chapters 5, 6 and 9). However in experiments 10 and 11 (Chapter 10) the effects of low sodicity were more marked. This was due to the types of wheat tested, because in experiments 10 and 11 only durum wheats which are sensitive to sodicity were tested, but in other experiments either only hexaploid (experiment 5) wheat or hexaploid together with tetraploid (experiments 3 and 4) wheats were tested.

The adverse effects of sodic soils on plants were associated with accumulation of higher Na^+ and lower K^+, Ca^{2+}, Mg^{2+} and lower K^+/Na^+ ratio in leaf sap (Chapters 5, 6, 7 and 8). The higher uptake of Na^+ and lower uptake of K^+, Ca^{2+} and Mg^{2+} and lower K^+/Na^+ ratio were directly associated with high pH, SAR and ESP and low WSA % (Tables 5.1, 5.2, 5.3, 6.1, 7.1, 8.1, 9.1 and 10.1). Measurements of ion concentrations and comparison with published values suggested that the adverse effects of sodicity were not due to mcironutrient deficiency or toxicity (Appendix 2, page no. 234).

Substantial improvements in seedling emergence %, survival % of plants with ears at maturity, growth and yield of wheat occurred in the sodic soils following treatment with PAM especially at medium and high sodicity levels (experiments 3, 4 and 5). This trend was not observed in all experiments at all sodicity levels. Responses to PAM (the difference in the % decrease in seedling dry weight between the +PAM and -PAM treatments) were often smaller at low sodicity level (Table 11.1), usually because the lowest level tested was insufficient to cause a substantial decrease in seedling dry weight (experiments 3 and 4) or grain yield (experiment 5). In experiments 2, 6 and 7 (Table 11.2), PAM also showed very slight increases, especially for seedling dry weight (experiment 2) and grain yield (experiments 6 and 7). This was possibly due to higher ESP in experiments 6 and 7, compared to the ESP levels in experiments 3, 4 and 5, so that plants may have faced a greater effect of exchangeable Na^+ than poor soil structure. In other experiments, especially at high ESP levels, the decreases in seedling emergence, seedling dry weight, (experiments 3 and 4), survival % and grain and straw yields (experiment 5) due to sodicity were much lower in the presence of PAM than in the absence of PAM (Table 11.1). This suggests that above an ESP of 40 to 50, the effect of exchangeable Na^+ was greater than the effect of poor structure, especially on grain yield (Tables 11.1 and 11.2). In sodic soils with ESP up to 40 or 50 as in experiments 3, 4 and 5, the effects of poor soil structure appeared to be greater than the effects of Na^+ (Table 11.1). These results are also comparable with the findings of Allison (1956), who concluded that above a critical ESP level (40 to 50 ESP in loam soil), growth of sweetcorn beyond the seedling stage is seriously inhibited due to the effect of sodium *per se*, even in the presence of improved soil structure. Below this critical ESP level growth appeared to be limited mainly by poor soil structure.

The effects of PAM were not similar on all plant characters. In some experiments (experiments 6 and 7) improved structure had no marked effect on number of tillers and

Table 11.1. Percent increase (+) or decrease (-) in seedling dry weight or grain yield over control values estimated to be due to physical and chemical effects (- PAM), chemical effects (+ PAM) and the difference between them. WSA % values show the percentage of water stable aggregates measured. Na^+ values are for the youngest fully expanded leaf (expts. 3 and 4) and the flag leaf sap (expt. 5). ESP values are those recorded at sowing

ESP	Low ESP			Medium ESP			High ESP		
PAM application	-PAM	+PAM	Difference	-PAM	+PAM	Difference	-PAM	+PAM	Difference
Experiment 3									
WSA % (at harvest)	61	95		38	91		33	80	
Seedling dry wt/plant	-1	0	+1	-18	-8	+10	-88	-8	+80
Na^+(actual value)	—	—	—	295	215	-80	—	—	—
ESP	18	18		29	32		39	39	
Experiment 4									
WSA % (at harvest)	62	80		46	79		40	85	
Seedling dry wt/plant	-22	-18	+4	-40	+13	+53	-40	-1	+39
Na^+(actual value)	—	—	—	193	148	-45	—	—	—
ESP	20	19		29	33		40	40	
Experiment 5									
WSA % (at harvest)	48	88		36	80		29	75	
Grain yield/plant	-14	-14	0	-25	-14	+11	-80	-25	+55
Na^+(actual value)	4	5	+1	52	38	-14	115	68	-47
ESP	15	15		29	28		44	46	

Table 11.2. Percent increase (+) or decrease (-) in seedling dry weight or grain yield over control values estimated to be due to physical and chemical effects (- PAM), chemical effects (+ PAM) and the difference between them. WSA % values show the percentage of water stable aggregates measured. Na$^+$ values are the actual values for flag leaf (Expt. 6) and % change over the control in shoot dry matter of seedlings at flag leaf stage (Expet. 7). ESP values are those recorded at sowing

Sodicity	High ESP		
PAM	-PAM	+PAM	Difference
Experiment 2			
WSA % (at harvest)	38	73	
Seedling dry weight	-64	-57	+7
ESP	48	46	
Experiment 6			
WSA % (at harvest)	26	87	
Grain yield/plant	-91	-86	+5
Na$^+$ (actual value mol m^{-3})	233	131	-102
ESP	52	48	
Experiment 7			
WSA % (at sowing)	38	73	
Grain yield/plant	-100	-99	+1
Na$^+$ (% over control)	+33	+13	+20
ESP	49	46	

fully expanded leaves, but on shoot height and shoot dry weight PAM had substantial effects. This suggests that at very high sodicity some plant characters were more sensitive to exchangeable Na$^+$ and others were more sensitive to poor soil structure.

The effects of PAM on plants at high sodicity can be attributed to increased soil aggregation (Tables 5.1, 5.2, 5.3 and 6.1) because WSA % was greater in the presence of PAM than in the absence of PAM (Tables 11.1 and 11.2). Morsey *et al.* (1991) also reported that PAM promotes aggregate stability to the soil. Other soil properties for instance, SAR and ESP were decreased at harvest by PAM, suggesting a reclaiming effect of PAM in sodic soils. Allison (1956) also found that in the 2 years after application polymers had a reclaiming effect equal to 1 ton/ha of gypsum in sodic soils. He also measured the WSA % in gypsum treated sodic soils. He observed that gypsum did not increase the degree of water stable aggregation over the untreated sodic soils. He noticed 15 % more yield of sweetcorn in gypsum plus polymer treated sodic soils than in polymer only treated soils.

The effects of PAM were associated with changes in ion concentrations accumulated by plants in leaf sap, grain and straw (experiments 3, 4, 5, 6 and 7). PAM increased concentrations of nutrient cations and K^+/Na^+ ratio and decreased Na^+ concentration in leaf sap, grain and straw dry matter of plants. This suggests that the increased soil aggregation might have caused sufficient aeration which may have enabled plants to take up nutrients and exclude toxic ions in sodic soils. This also suggests an indirect effect of improved soil structure on plants, by decreasing the uptake of toxic ions (Na^+) and increasing the uptake of essential nutrients (K^+, Ca^{2+} and to some extent Mg^{2+} and micronutrients) and K^+/Na^+ ratio. Similar ideas have also been suggested by Singh and Totawat (1994), who reported that poor structure of sodic soils also influences the uptake of nutrients by plants. It is also clear from the FAO (1984) report that soil oxygen supply is critical to active absorption. Lack of O_2 hinders production of energy by roots and therefore limits nutrient uptake.

In experiments 2, 3, 4, 6, 7 and 8 conducted with the polymer, most of the varieties tested showed a positive response to PAM. However there were some varieties (Avalon, and KTDH-19) which responded either negatively or they showed a very slight positive response to PAM (Experiments 2, 3 and 4). Bakhtwar did not show a similar trend in all 3 experiments (2, 3 and 4). It showed a positive response to PAM in loamy sand soil (experiment 3) but not in clay loam soils (experiments 2 and 4). Varieties which responded positively to PAM at high sodicity at the seedling stage (such as Kharchia-65) also responded positively at later stages, especially for straw and grain yields (experiments 3, 4, 5, 6 and 7).

Although this trend was not consistent in all experiments, the improved performance of most varieties and genotypes was generally associated with lower Na^+ and higher K^+ and higher K^+/Na^+ ratio in leaf sap and shoot straw (Chapters 5, 7 and 8). However some varieties showed improvement in emergence and growth, but they did not show lower Na^+ (Q-19) and higher K^+ (NIAB-20) and K^+/Na^+ ratio (Bakhtwar) (Chapter 5) in their leaf sap in the presence of PAM. Amongst the durum (tetraploid) wheats tested, genotypes with the Kna1 discriminating gene (R112$^+$ and R173$^+$) showed greater response to PAM than those without the gene in both experiments 3 and 4 (Chapter 5). The greater response of these genotypes in the presence of PAM was also associated with lower Na^+ and higher K^+ and K^+/Na^+ ratio in leaf sap. This indicates that K^+/Na^+ discriminating trait serves even better under sodic soil conditions in the presence of improved structure, possibly because both problems of sodic soils i.e. high Na^+ and poor structure are addressed.

Apparently these results provide some indications, however detailed field investigations seem to be necessary and interesting too.

11.5 Do the effects of sodicity and PAM vary with soil types ?

It is evident from Tables 5.2.1 and 5.3.1 and Figures 5.2.1 and 5.3.1 that sodicity decreased emergence and growth (Tables 5.2.4, 5.2.5, 5.3.4 and 5.3.5) of seedlings more in loamy sand soil (Experiment 3) than in clay loam soil (Experiment 4). This was possibly due to the differences in soils, as the loamy sand soil had markedly lower organic matter and nitrogen % (Tables 5.2 and 5.3) than clay loam soil. This trend was not observed in experiments 8 and 9 (Chapter 9), where sodicity showed adverse effects on plants in both (loamy sand and clay loam) soils. These different responses could be due to differences in environmental conditions. Experiments 3 and 4 were conducted in a glasshouse with no control of temperature (Appendix 1), whereas experiments 8 and 9 Section 9.3.2) were conducted in a growth room with a controlled environment.

Differences in the effects of sodicity in two soils in the glasshouse but not in the growth room were generally associated with differences in ion uptake. Under glasshouse conditions seedlings grown in loamy sand soil had higher leaf Na^+ and lower K^+/Na^+ ratio and other cation concentrations than the seedlings grown in clay loam soil (Tables 5.2.3a, b and 5.3.3a, b). On the other hand in Experiments 8 and 9, where there was no difference in the effects of sodicity in the two soils, the plants grown in the growth room generally had similar concentrations of ions in their flag leaves (Tables 9.3 and 9.7). These differences in ion concentration could be due to differences in transpiration which might have increased translocation of Na^+ ions from roots to shoots of the plants grown in the loamy sand soil in Experiment 3 and in loamy sand and clay loam soils of Experiments 8 and 9. It has also been reported by Ayoub and Ishag (1974) that the effect of soil sodicity on plants depends on atmospheric temperature and humidity.

The effects of sodicity on texturally similar soils were also different. The clay loam soil collected from Henfaes farm (Experiments 2, 5, 6 and 7) was found to be more sensitive to high sodicity for plants than the clay loam soil collected from Caeglanmor field (Experiment 4). This was possibly due to differences between types of clay, organic carbon and nitrogen contents. The soil of Henfaes farm field was low in organic carbon and nitrogen and had slightly higher clay content than the soil of Caeglanmor field.

As the effects of sodicity on different soils were variable, the effects of PAM were also variable. The effects of PAM on plants were greater in soils with low organic matter (Experiments 3 and 5) than in the soil with slightly more organic matter (Experiment 4). This indicates the superior performance of synthetic polymer (PAM) in the absence of organic matter and in soils sensitive to sodicity. The response to PAM was also greater in the loamy sand soil than in the clay loam soil (experiments 3 and 4 (Chapter 5)). Greater response to polymers in sandy soils than in clay and silty soils has also been reported by other workers (Laws, 1954; Jacobson and Swanson, 1958). Allison and More (1956) reported that a minimum of 8 to 10 % clay is essential for maximum aggregation by polymers. However to cover the increased surface area as a result of increasing clay content requires increases in polymer concentrations.

11.6 Can using transplanted seedlings help to improve plant performance on sodic soils ?

In the sodic soil treatments transplanted seedlings successfully survived up to maturity (Chapter 7, 8 and 9), and they had higher grain (Chapter 9) and straw (Chapters 7, 8 and 9) yield than seed sown plants (experiments 8 and 9). This was possibly due to them completing the sensitive germination and emergence stage in a non sodic environment.

It was expected that the improved performance of transplanted seedlings may have an association with lower Na^+ and greater K^+ uptake, and possibly higher K^+/Na^+ ratio. Although Ca^{2+} and Mg^{2+} were slightly higher in the leaf sap of transplanted seedlings, there was no clear evidence of less Na^+ and more K^+ and higher K^+/Na^+ ratio (Chapter 9) in transplanted seedlings. This was possibly because the longer roots of transplanted seedlings came into greater contact with the soil than seedlings sown from seeds and hence they might have absorbed more Na^+. The low grain yield of transplanted plants in experiments 6 and 7, than in experiments 8 and 9 was not clearly associated with leaf Na^+, K^+ and K^+/Na^+ ratio. Several factors may have contributed to these differences, for example differences in soils, sodicity levels, methods of sowing and growth conditions. In experiments 6 and 7 plants were grown in a glasshouse with no control of light and temperature, whereas in experiments 8 and 9 (Chapter 9) plants were grown in a growth room with a controlled environment. Different plant stages were used to grow plants in experiments 8 and 9, whereas in experiments 6 and 7 seedlings of identical age were used to grow plants.

Twelve, 16 and 21 day old seedlings proved to be suitable ages for wheat seedlings to be transplanted (experiments 6, 7, 8 and 9). However, pre-germinated seeds were very sensitive to sodicity (experiments 8 and 9). The reason for this could be that at this early stage there were no food reserves left in the seeds, and they also could not utilise water and nutrients from soil easily through their undeveloped root system.

Overall the results of these experiments provide some evidence that plant performance can be improved using the transplanting method of sowing. However, further research is needed to investigate the technical and economic feasibility of this technique under saline and sodic field conditions.

11.7 A Final Word to the Farmer and researcher

It is concluded from this study that generally in sodic soils with ESP up to 40 or 50 poor soil structure may be the primary cause of low wheat yield, and above this range high exchangeable sodium may be the major cause of low wheat yield. Hence it is suggested that in sodic soils with an ESP up to 40 or 50 the poor structure needs to be improved. The adverse effects of sodicity with an ESP above 40 or 50 even in the presence of improved structure, indicate that the exchangeable sodium of such soils needs to be replaced before the improvement of soil structure. In Pakistan gypsum is available on a large scale, but due to the arid climate most of the soils are deficient in organic matter. Hence it is difficult to improve the structure of sodic soils in this way. The results of this study suggest that PAM can be selected to perform the job of improving soil structure in sodic soils.

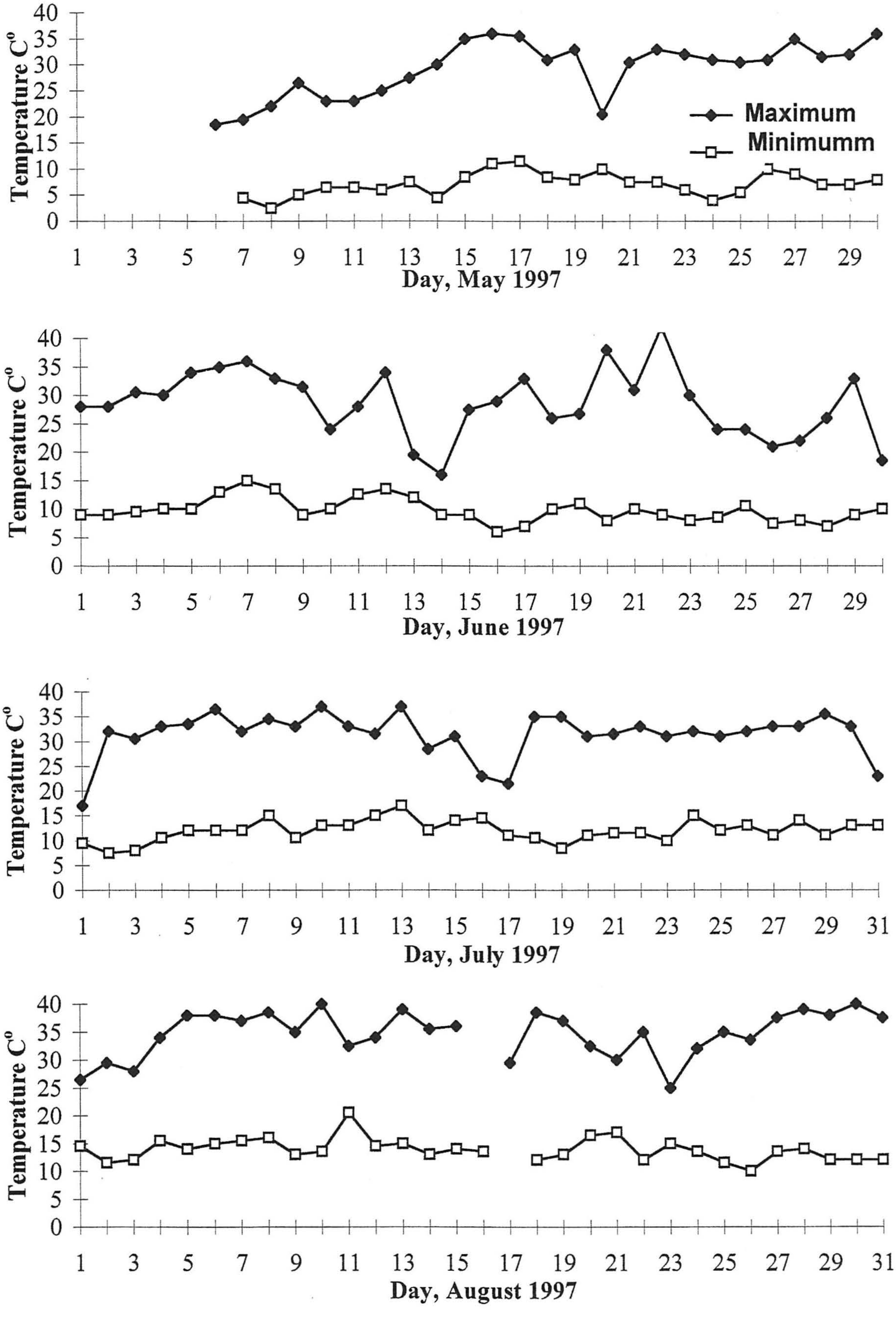
In Pakistan most of the salt-affected soils are saline-sodic in nature with very low organic matter and variable texture. Although in this study PAM was tested in different soils, it is still necessary to test polymers in different types of sodic soils in field conditions. Although earlier workers have confirmed that synthetic polymers are that the degradation of PAM might occur due to the direct or indirect effect of sun light, and cultivation practices etc. In general, summers in Pakistan are very hot, especially in upper Sindh region, where temperature sometimes exceeds 40 °C. The high cost of PAM may also cause problems, especially if it has to be applied frequently to remain effective. Although earlier workers (Martin, 1953; Laws, 1954) have suggested that polymers are best mixed with soil at rates varying from 0.02 to 0.2 %, the results of this study suggest that at least 2 tons/acre of PAM would be needed for improving the structure of sodic soils within the furrow slice space. However, PAM may become useful in sodic soils with a superficial sodicity problem. This detailed field research will contribute more to find out the lowest possible, economical concentration of PAM to be used in these soils.

The success of transplanted wheat seedlings in this study suggests that by using traditional (transplanting) techniques plant performance in salt-affected soils can be improved. It is also a fact however that it would impose an additional management burden on farmers, because for applying this technique farmers need to grow wheat nurseries and transplant them into the field. In developing countries rural communities always appreciate the benefits of integrated traditional techniques which they can easily adopt. So it seems to be useful to suggest that agricultural engineers put effort to invent machines that can transplant wheat into the field.

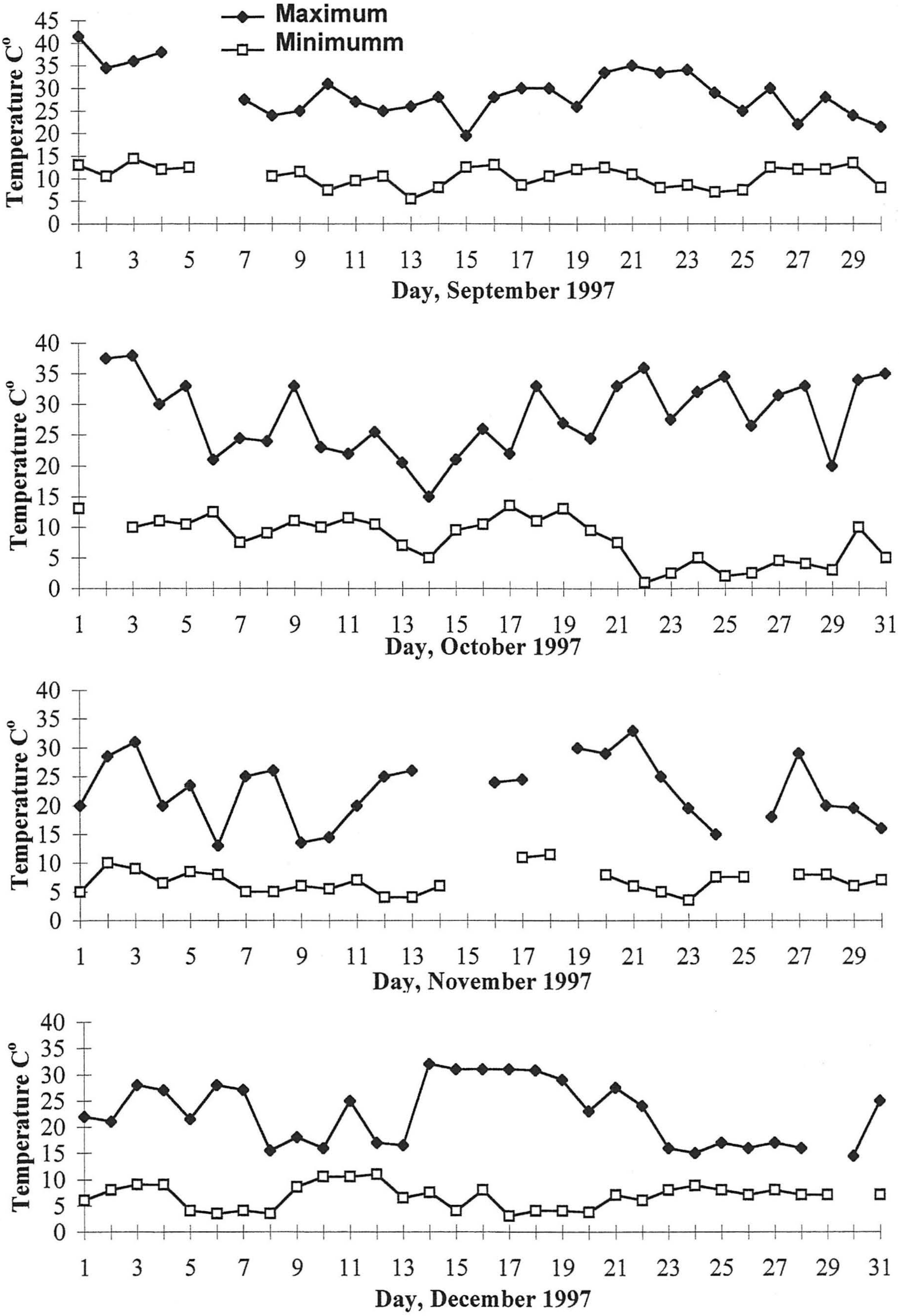
This study also provided some evidence that improved production can be achieved by developing varieties resistant to salts as well as poor soil structure. Hexaploid wheat varieties such as Kharchia-65 and durum wheat genotypes with the K^+/Na^+ discriminating gene ($R112^+$ and $R173^+$), which are tolerant, should be incorporated into future breeding programmes to breed a wide variety of locally adopted wheats tolerant to sodicity as well as poor soil structure. It may also be useful to produce new dual purpose varieties.

''We need to keep our land ' in good heart' although it is feeding us-not only this year, next and the one after that, but as long as the sun shall shine'' (Lawrence, 1989).

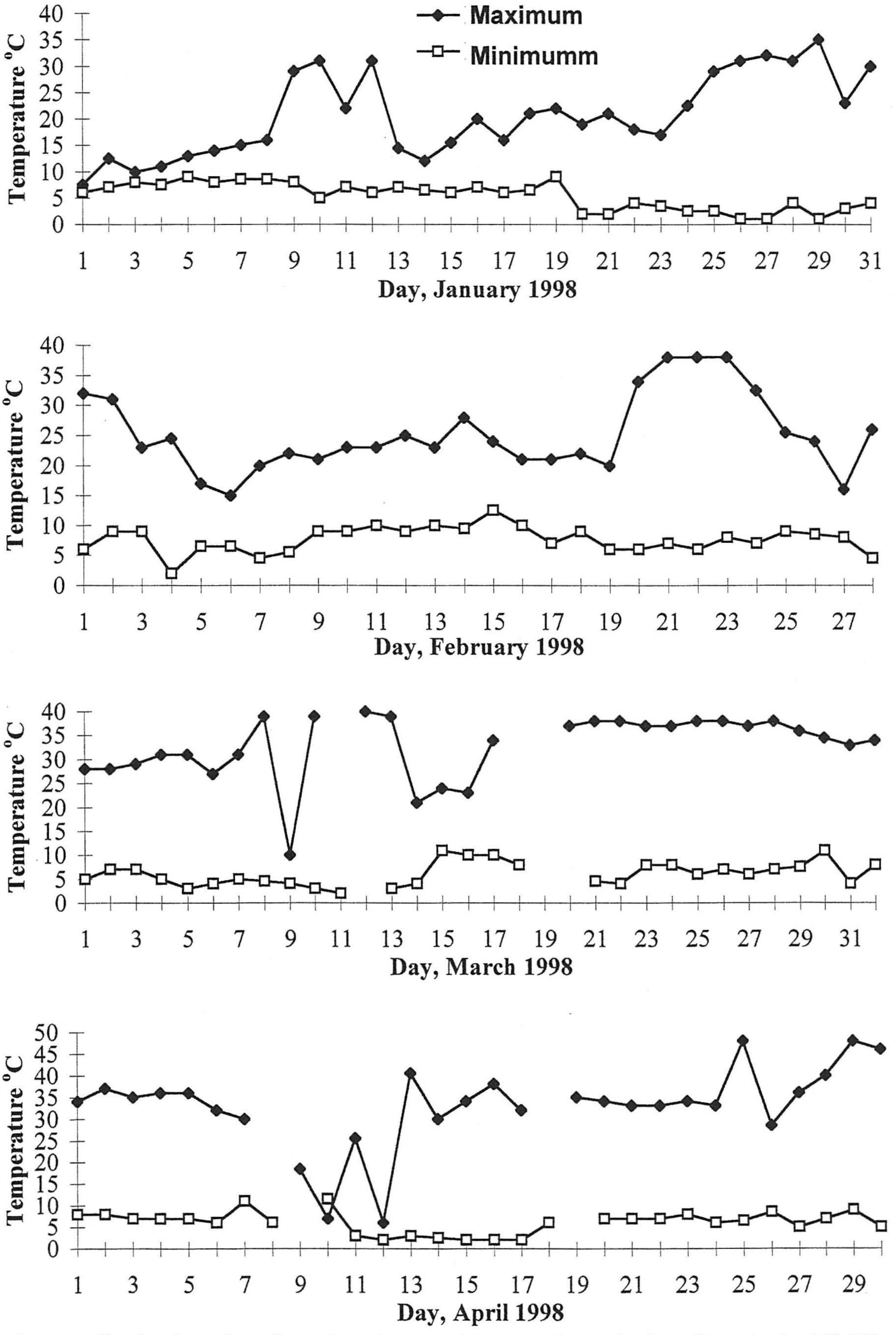
Appendices



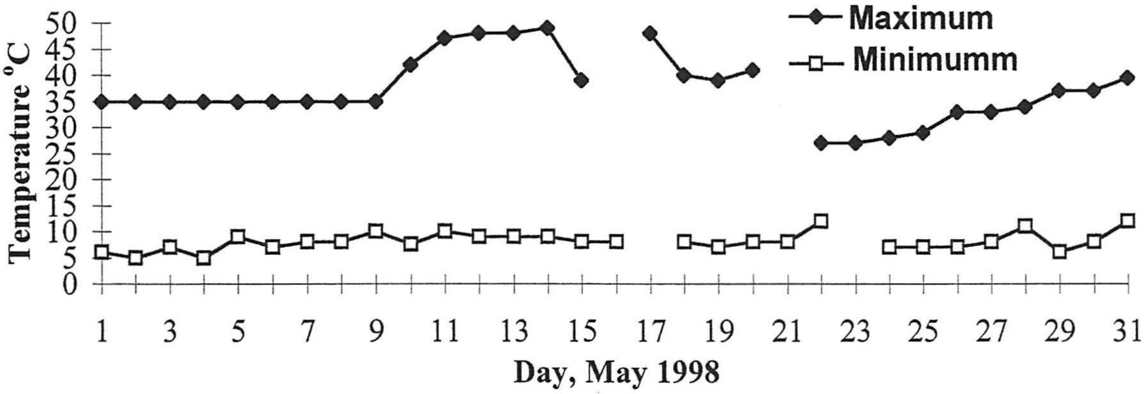
Appendix 1. showing the glasshouse temperature during the study (1997).



Appendix 1. showing the glasshouse temperature during the study (1997).



Appendix 1. showing the glasshouse temperature during the study (1998).


Maximum
Minimumm
Temperature °C
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29
31
Day, May 1998

Appendix 2a. Deficient, sufficient and toxic levels of Micronutrients concentrations measured in mature leaves (Landon, 1984)

	Concentration in ppm		
Nutrient	Deficient	Sufficient	Toxic (excess)
Cu^{2+}	< 4	5 to 50	> 20
Fe^{2+}	<50	50 to 250	>400
Mn^{2+}	<20	20 to 500	>500
Zn^{2+}	<20	25 to 150	>400
Mo	<0.1	0.5	not suggested

Appendix 2b. Low, medium and high levels of Organic matter content (% of soil by weight) of soils suggested by Landon (1984)

<2 = Very low

2 to 4 = Low

4 to 10 = Medium

10 to 20 = High

>20 = Very high

Appendix 2c. Low, medium and high levels of N (% of soil by weight) content of tropical soils suggested by Landon (1984)

<0.1 = Very low

0.1 to 0.2 = Low

0.2 to 0.5 = Medium

0.5 to 1.0 = High

>1.0 = Very high

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